VOLUME 83 NO. AT1
JULY 1957

JOURNAL of the

Air Transport Division

PROCEEDINGS OF THE

AMERICAN SOCIETY OF CIVIL ENGINEERS

AMERICAN SOCIETY OF CIVIL ENGINEERS FOUNDED 1852

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AT,BD,CP,CO,HW,IR,SU,WW,PL.

Journal of the

AIR TRANSPORT DIVISION

Proceedings of the American Society of Civil Engineers

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Journal of the

AIR TRANSPORT DIVISION

Proceedings of the American Society of Civil Engineers

COLD REGIONS RESEARCH BY THE U.S. CORPS OF ENGINEERS*

Robert R. Philippe[1]
(Proc. Paper 1323)

FOREWORD

Symposium on Cold Regions Air-Transport Problems

Polar air routes and air bases north of the Arctic Circle have added a new and exciting dimension to the already scintillating field of air transport. Developments on this frontier have been made possible through the cooperative efforts of operating personnel and engineering technologists. In the Symposium, presented at the October 1956 Convention of the Society (of which this paper is a part), the part played by workers in an exacting field is dramatically written in statements of problem areas, in the results of their research, and in their hopes and anticipation of future application of their findings.

The five papers (Proc. Papers 1323 through 1327) and attendant discussions represent the most advanced knowledge available on cold regions air transport. The papers have been selected to take advantage of the special abilities of the authors, each of whom is an emminent authority, and to indicate for readers the opportunities and problems in this area of military and commercial transport significance.

SYNOPSIS

In this paper the author presents a comprehensive outline of the Corps of Engineers' research and development program in the Arctic. Work in progress in Greenland is set forth in detail. Air, surface, and subsurface transport problems are discussed against a background of available materials, power sources, and weather.

Note: Discussion open until December 1, 1957. Paper 1323 is part of the copyrighted Journal of the Air Transport Division of the American Society of Civil Engineers, Vol. 83, No. AT 1, July, 1957.

*Paper prepared for presentation at the Convention of the Society at Pittsburgh, Pa., October 16, 1956.

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INTRODUCTION

The assault of our northern frontier is proceeding at an accelerating rate. For example, plans for the International Geophysical Year 1957-58 provide that thirteen nations will maintain about 150 stations in the Arctic for scientific investigations in meterology, geomagnetism, aurora, ionospheric physics, solar activity, cosmic ray, glaciology, seismology, and gravity. The people engaged in these activities will suffer hardships but in general they will conduct this work with ease and comfort when compared to the conditions endured by the explorer of old. Much of this change can be attributed to improvements in transportation, both by air and on the ground. Perhaps the extent to which this has occurred can be judged by the fact that in one work week in July 1956 leaving Washington on Monday and returning on Friday, it was possible to visit and inspect six major bases in New Foundland, Labrador, Baffin Island, and Greenland, and to conduct an inspection of research and development activities which are stretched out across two hundred miles of the Greenland Icecap east of Thule.

Although developments in aircraft contribute mightily to this growing capability, improvement in transportation attributable to these developments is not exclusively applicable to the Arctic. On the other hand there has been a marked improvement as a consequence of the development of new engineering methods and techniques peculiarly applicable to conditions which occur in the Arctic. The principal objective of this paper is to indicate the purpose of these activities.

Two elements to our well-being became essential during World War II: an air route to Europe, and the defense of Alaska. To assure these, the United States and Canada constructed military bases and support facilities in the subarctic reaches of Northern Canada, New Foundland, Labrador, Baffin Land, Greenland, and Iceland. In Alaska and Northwest Canada the construction of the Alcan Highway attracted the greatest public interest but there were numerous airfields and other facilities as well. With the advent of warfare in Korea and the period of uneasiness associated with it, there was a rapid enlargement of some of the existing facilities and the construction of new ones. The military bases created under this program, such as Thule, BW8, Goose Bay, Ladd, and Eilson, stand as monuments to the fact that we have learned to build permanently and well in the Arctic.

As significant as these accomplishments may be, they have been made at great costs spurred by the justification of national defense. Certainly such efforts cannot be justified on the basis of economic prospects and natural benefits. No territory has yet been exploited successfully until men have learned to use indigenous materials for the bulk of construction requirements. Conversely, it is held to be axiomatic that any given region cannot continue to survive for long on the basis of importing a substantial portion of the materials needed for construction. If the precepts of this axiom are true, then we must learn to make maximum use of the indigenous materials of the Arctic: snow, ice, and frozen ground.

At first blush this may appear impossible, but when one realizes that snow under the right conditions is as substantial as a "soft sugar" sandstone, ice has many qualities of a desirable rock, and that frozen ground, while frozen, has many desirable structural qualities, then the feasibility of this concept increases. This calls for a change in approach; to look for conditions of these materials and temperatures conducive to lasting stability. As a result we are

beginning to consider certain areas, heretofore regarded as unfavorable, as being actually attractive for construction purposes. The glaciated regions of Baffin Land, Ellesmere Island, Greenland, Iceland, Spitzburgen, Franz Josef Land, Novaya Zerulya, North Land, and the new Siberian Islands, and depots on the Asiatic Continent and the Arctic Ocean are offering new possibilities.

Motivated by these concepts the Corps of Engineers has been engaged in investigations for the past fifteen years aimed at improving engineering methods and techniques to facilitate the establishment and maintenance of large facilities in support of military operations in the Arctic. Although these have application in many areas within the Polar regions, our more recent efforts have been concentrated, but not confined, to Greenland. It serves the immediate purpose to confine this presentation to this Island but only as the outstanding example of that which can be done.

The Location of Greenland

General

As a landform Greenland provides a platform centering roughly about longitude 40° West from latitude 60° North to 83° North, a distance of 1500 miles. It is the landform wedge that separates the North American continent from Northern Europe and Asia. A locus of points 2500 miles from the crest of this island prescribes a line passing through Gibraltar, Corsica, Budapest, Kiev, and contains all of Siberia which drains to the north. On the opposite hand, the line passes through Savannah, St. Louis, Seattle and Seward. Hence the major portion of the industrial might of the world lies within a 2500-mile range of Greenland. Furthermore, Greenland is unique in this respect. The potentialities of Alaska under the same terms is fractional by comparison.

Discussion

The advantages of location, though obvious, have been considered offset by the severity of the climate and the country. Until recent years there has been no serious consideration given to exploiting the advantages of Greenland's location because the hardships were thought to be unsurmountable. Operations during the last war and the subsequent establishment of Thule as an air base upset this conclusion to a degree, but it remains that Thule is essentially unsatisfactory due principally to its isolation. Furthermore the establishment of a series of mutually supporting bases of similar character in this region of the world is probably prohibitive as to costs.

Conclusion

Accepting the obvious advantage of Greenland's geographic location and admitting to a desire to exploit it, it is concluded that it is necessary to find new, simplified, and less expensive means of bringing this about. In addition, the converse conclusion should also be considered. Is it not possible to find means of exploiting this locational advantage? It was for the purpose of resolving these questions that the Army initiated a research and development program in 1952, a major portion of which is now being executed by the Corps of Engineers.

The Character of Greenland

The Landform

Greenland has an area of approximately 850,000 square miles, 750,000 of which are covered with an icecap, or more exactly, a snow field. The Island, which is about 1500 miles long and 650 miles at its widest, has a perimeter of moderate mountains which are fairly continuous and of moderate height (2,000 to 3,000 feet). These mountains form the lip of a broad and overall basin which is filled with snow and which tends to accumulate so that the crest of the icecap is at elevation 10,000 feet. Seismic studies indicate that this snow is 9,000 to 11,000 feet deep at the maximum so that some of the landform in the basin is thought to be below sea level.

The Icecap

This high mass of accumulated snow is in a state of unstable equlibrium. As snow load is accumulated on the surface two general reactions take place; (1) the snow under the surface is densified by the addition of load and (2) the mass as a whole yields in slow plastic movement with outward evidence as glaciers, melting at the warmer and lower elevations, and other forms of movement and ablation.

The Nature of the Surface

For all but the very perimeter of the icecap the surface is that of a snow desert; broad unending vistas of snow almost level, with only the mildest of undulations caused by very flat snow dunes. Furthermore, all but day-old snow is hard so that absolute freedom of movement by most track-laying vehicles has actually been experienced. In contrast, the peripheral zone, generally only a few miles from the edge, is a zone of distress where the mass in motion draws into flows between mountains as glaciers. These distortions cause cracks which, in the uplands of the drawdown, are rapidly closed over by falling snow. This process, in an extreme, will form a snowbridge over a crevasse 50 feet wide and 200 feet deep which will be undetectable by eye. Sometimes these snow bridges are unstable; the danger is obvious. The magnitude of these mass motions is in terms of inches to a few feet a day.

The Subsurface Conditions

In the center of the icecap the process of densification due to added snow load causes a process of consolidation such that snow, which at falling has a density of 0.25, will achieve a density of 0.75 by the time it is covered with 100 feet of new snow. This process of densification continues but the density never reaches an ultimate, because of a certain amount of entrapped air. Hence that which comes to the surface at the edge of the icecap is glacial ice, a densified blue ice which contains entrapped air under pressure.

Permafrost

The perimeter of land, which during the summer is snow-free, is permanently frozen to great depths, of the order of 1,000 feet. During the heat of summer the surface of this frozen mass is thawed and the soils often turn

into mud which is unstable as foundations for roads and buildings. These conditions require special treatment, design, and construction to produce satisfactory structures.

Weather

The existence of the Icecap and its weather regime are intimately interwoven. The amount of snowfall is not great, averaging less than three feet a year. Above an elevation of a few thousand feet, however, the temperatures hardly ever rise to thawing, with the result that all snow that falls accumulates. In winter, sub-zero (to -75°F) temperatures prevail with winds of 100 miles per hour a common occurrence. Below 3,000 feet, thawing in the summer becomes more prevalent at lower elevations. At Thule there are pleasant summer days with temperatures in the high 50's. The firn line, where more snow falls than melts, is generally within a few miles of the edge of the icecap. There is a pattern of down-slope winds associated with the icecap known as "catabatic winds," which at the surface generally overwhelms the broader weather regime. As may be expected, the region breeds weather. The weather, however, is not all bad and there are many periods of cold clear weather with mild to moderate winds. The fact that the sun shines 24 hours a day in summer and never shines in winter is significant.

Sea Ice Conditions

The sea approaches to Greenland are influenced and controlled by sea ice conditions. In summer the west coast is navigable usually well above Thule, whereas the east coast, which is never free of ice, has been penetrated by heavy ships only half way up the coast. In winter a short strip along the southern portion of the west coast remains ice free, whereas the east coast is ice bound. These conditions are significant with respect to sea approaches.

Population

The total population of Greenland is 22,000, mostly Greenlanders in the south. There is a group of Thule Eskimos in the northwest which numbers in the hundreds.

Political

Greenland is a benevolent democracy and is considered by the Danes to be an integral part of Denmark. Curiously, the Greenlanders have no representation in the Danish Parliament simply because the Greenlanders thought this superfluous and unnecessary. The Danes protect the political economy of Greenland very jealously and are embarked upon a plan of gradual improvement of the island's economy. Our forces and bases in Greenland are regionally separated and no mingling of personnel or economy is permitted. The Danish Government has taken a very cooperative, interested, and friendly attitude toward our research and development. It is to be remembered, however, that the United States has relinquished all claims it might have had to northern Greenland when, in purchasing the Danish West Indies (Virgin Islands), the Secretary of State formally stated that the United States would interpose no objection to the extension of Danish economy and government to the whole of Greenland (6 August 1916). We are discussing that which has been declared to be Danish territory.

Corps of Engineers' Research and Development Program

History

In the introduction there is reference to the bases established on land in the Arctic regions with further indication of our interest in the potentiality of building on and of snow and ice. Active interest in this potentiality was initiated in 1952 by General Sturgis, until recently Chief of Engineers, then acting as Air Installations Officer. The program of investigations designed to build airfields on the Greenland Icecap was very limited and one of opportunity, tying a few men to field efforts conducted jointly by the Air Force, the American Geographic Society and others. Opportunity to expand these modest efforts was presented when in 1953 the Transportation Corps launched into a study of "transporting large tonnages of cargo and personnel across the Greenland Icecap." This concept of transporting across the Icecap visualized establishment of bases in snow-free areas such as Peary Land. This limited concept was broadened when, in 1953, a program was evolved to develop engineering methods and techniques to establish, maintain, and support large facilities and military operations on or across the Icecap. A limited amount of work was done in the summer of 1953 under the "transport" concept. Full-blown efforts were made by the Corps of Engineers in 1954, 1955, and 1956 and much greater efforts are contemplated for the immediate future. The major effort is that of developing these engineering techniques with the concept of transport still an essential ingredient. A major contribution has been made by the Air Force both in logistical support and encouraging interest. Amongst the Technical Services of the Army, Signal, Quartermaster, and Ordinance have participated.

Outline of the Program

The Corps of Engineers' program consists of 33 tasks, 7 of which are not active. These tasks represent individual engineering problems which, when all are solved, will permit complete and integrated engineering designs and estimates for whatever requirements these acquired abilities will generate.

Accomplishments to Date.

Rather than indulge in a recitation of the Corps of Engineers' program, it will be described in terms of accomplishments, embellished in terms of future plans. The groupings are for ease of presentation.

1. In support of on-the-surface movement.

a. Land approaches. Several units of trial roads have been constructed near Thule with improved techniques over the permafrost, raised to minimize snow drifting and placed to take maximum advantage of the characteristics of permafrost as revealed by basic studies of this phenomenon. Sufficient observations have been made to fix design methods and to accurately estimate costs.

b. Onto the icecap. An approach road onto the icecap built of selected rock-earth mixtures has been extended a distance of 3.2 miles from the Icecap edge at Thule Takeoff (Tuto). This road, so constructed, permits wheel vehicles to transcend the zone of heavy melt where no vehicles, wheel, track, or sled, can operate with ease. Design requirements and fixed costs can be estimated.

c. Transfer points. Pier-like structures have been built at the end of the approach road onto the Icecap to permit the rapid transfer of loads from wheeled vehicles to tractor-drawn sleds operated over the snow surface.

d. Snow compacted roads. Techniques have been developed for constructing compacted-snow roads which would be satisfactory for the operation of vehicles. It has been judged however, that such roads would be impractical, if not impossible, to maintain over long distances due principally to the inherent development of the icecap which would require raising such a road about three feet a year. The concept of subsurface roadways, to be discussed later, is so attractive that no extensive surface-road system is likely.

e. The crevasse problem. Crevasse characteristics, including detection, have been studied. The occurrence and movements of crevasses have been associated with the mass characteristics of glacial drawdown. Much information has been gleaned on the width, depth, bridging, and spacing of crevasses. A crevasse detector which was devised in Greenland has found its way to the Antarctic. The elements of this progress are essential to any system of surface travel through the crevasse zones. The means are now available whereby the perils of crossing crevasse zones can be reduced. Plans of the Corps of Engineers contemplate improving the rate at which this can be done.

f. Trafficability. The physical properties of the surface snow, to depths of 15 feet, have been extensively explored over the northern half of Greenland as well as many other similar surfaces including the Antarctic. A school for glaciologists was held in Greenland during the summer of 1955 to assure utilization of uniform methods of data collection among personnel of the Western nations engaged in IGY studies, particularly in the Antarctic. In addition, extensive observations of the trafficability of track and wheel vehicles have been made. No wheeled vehicles will operate on the snow, almost all tracked vehicles do; the limit being determined generally by the towing capacity.

g. Navigation. All major problems associated with navigation on the Icecap have been solved. A vehicle gyro-compass has been developed. A vehicle-position indicator is also available. A wire-guidance system has been perfected which, with suitable apparatus in the vehicle, gives position with respect to an energized wire or wires laid in the snow. Sixty miles of system is installed, another 140 miles is contemplated by the end of the summer of 1957. A servo-steering mechanism is considered possible.

h. Prime movers. Heavy tractors (D7 and D8) have been modified for over-snow operations by winterizing and providing low-ground-pressure tracks. To date, these are the only heavy-duty prime movers which have been found satisfactory either in Greenland or the Antarctic. These, however, are too slow for ultimate use and if the need for over-surface transport develops, special-purpose prime movers will have to be devised.

2. The subsurface concept. The insurmountable difficulties of surface movement associated with the mass motion of the Icecap environment and the weather has forced the search for other concepts. Thoughts which undoubtedly spring from the Eskimo's ability to survive, lead one to ideas of subsurface tunnels, roadways, and structures to accomplish the same purpose. The construction of Camp Central by the French and the ACW stations by the Corps of Engineers for the Air Force in 1953 provide outstanding evidence in support of these views. It is now thought that any valid approach to the

fulfillment of the overall mission must be based upon subsurface construction within the Icecap proper.

a. Approaches. Reconsidering the approaches to the Icecap, roads will be used over snow-free land, then all similarity stops. The motion of ice ramps and cliffs at the edge of the Icecap are known from study of these basic movements at several locations near Thule. Two trial tunnels leading from the land directly into the glacial ice have shown such efforts to be very cheap and produce stable and satisfactory results. There will be added efforts during the next two years to develop these mining techniques in glacial ice, with tunnels and chambers in ice a few miles long well within our present research and development resources. It is thought possible to tunnel through glacial ice, beneath crevasses, to the crevasse-free area before coming near the surface. This can be done at a fraction of the cost of tunneling in rock.

b. Subsurface roadway. Upon approaching the surface in the crevasse-free area a roadway would be constructed by excavating a trench approximately 14 feet wide in snow and roofing that trench with snow. A temporary arch form would support snow blown back over the form for a few days after which the form would be removed. This has been demonstrated. Trial systems several miles long have already been built at Fist Clench, two hundred miles out on the icecap. Enough work has been done to indicate that such subsurface tunnels could be built for less than $2,000 per mile in Greenland.

3. Other engineering structures. Beyond the application for roadways, many other subsurface structures are thought simple, cheap, and feasible; some have been tried and more are planned.

a. In glacial ice. Arched chambers have been excavated in glacial ice roughly 65 x 65 x 23 feet. Our studies indicate arch spans over 100 feet are possible and will be tried in the coming two years. The temperature in such chambers remains constant at about 10°F. Investigations under way will include storage of equipment, food, and petroleum products in these chambers. Also contemplated is the design of a shelter set in such a chamber, heated and properly ventilated to permit human occupancy.

b. In snow. Unsupported subsurface arches in snow to 75 feet in width have been tried and found adequate and arches 100 to 115 feet are thought feasible. The temperature is constant and subfreezing at -13°F. This would permit the construction, on a limited life basis, of warehouses, garages, small hangars, POL storage, and many other facilities simply by excavating such chambers. The trials completed and contemplated are designed to demonstrate the feasibility of these concepts. In both cases the maximum can be accomplished with a minimum of imported material.

4. Power sources. A major hurdle to be topped is the lack of developable conventional sources of power in Greenland. There are limited resources of poor coal which, at the moment, are inaccessible; but which could be developed if communications are established. Undeveloped sources are wind, sun, tides, and cryo-electric. These are natural conditions for applications of nuclear power.

a. Pipelines. A study of the feasibility of installing pipelines in connection with the systems previously described has been completed, and it appears that there is no basic reason why pipelines cannot be installed. These can be placed on the surface or in subsurface roadways. Pumping stations and storage facilities have been studied with adoption of existing systems thought possible.

b. Undeveloped sources. Studies of the basic and peculiar characteristics of wind, sun, and tide have been made. Experimental wind generators have been installed but the feasibility of such a source would depend upon a widespread inter-connected system to distribute load to demand. Strangely enough, solar systems look encouraging because of twenty-four hours' of sunlight coinciding with the peak of activity in the summer. Tide is not thought encouraging. A system using mined snow which by gravity moves a chainless belt activating generators (a cryoelectric system) has good calculated efficiencies but is too costly to "try."

c. Nuclear sources. A study of the application of nuclear power sources has been completed which indicates this region to be a most profitable installation once the demand is developed. A pool-type reactor using an elementary reactor as a source of heat for melting snow to produce large quantities of hot water is under study. Hot water is a precious commodity for which many applications are visualized once a source is created.

5. Air Fields. On the Icecap, some two hundred miles from Thule, airstrips have been constructed by the simple expedient of compacting the surface snow. One runway was built in 1953, another in 1955. The latter of these was used by wheel-mounted C-47, C-54, and C-124 aircraft operating in some numbers. The plans for the future contemplate the rehabilitation of the runway at Fist Clench and maintenance of the runway for a twelve months' period.

6. Facilities planning. Problems of facilities and layout and related matters of water supply and waste disposal are all receiving attention and a basis of planning is fixed with respect to these factors.

7. Basic studies. Although discussion of this program has been presented on the basis of the development of an engineering approach, there have been studies of the basic physical properties of snow, ice, and frozen ground which constitutes part of the overall Corps of Engineers' research and development program.

CONCLUSIONS

The capacity to establish and maintain facilities and large scale operations in Arctic regions has been demonstrated through the Corps of Engineers' research and construction programs. Already preliminary discussions have been initiated with engineers and contractors on the applications of the findings of this program to construction problems in Arctic areas. The die is becoming cast. The capacities that have been demonstrated are generating greater demands.

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TESTING OF A COMPACTED SNOW RUNWAY*

James A. Bender**
(Proc. Paper 1324)

FOREWORD

Symposium on Cold Regions Air-Transport Problems

Polar air routes and air bases north of the Arctic Circle have added a new and exciting dimension to the already scintillating field of air transport. Developments on this frontier have been made possible through the cooperative efforts of operating personnel and engineering technologists. In the Symposium, presented at the October 1956 Convention of the Society (of which this paper is a part), the part played by workers in an exacting field is dramatically written in statements of problem areas, in the results of their research, and in their hopes and anticipation of future application of their findings.

The five papers (Proc. Papers 1323 through 1327) and attendant discussions represent the most advanced knowledge available on cold regions air transport. The papers have been selected to take advantage of the special abilities of the authors, each of whom is an emminent authority, and to indicate for readers the opportunities and problems in this area of military and commercial transport significance.

ABSTRACT

This paper consists of a comprehensive report on the field testing of a snow runway built on the Greenland Ice Cap by the U.S. Corps of Engineers. The author describes in-place, laboratory, and large-scale testing of snow for this runway. Test methods and results obtained are set forth in detail. An appendix describes the effects of temperature and age-hardening on the strength of snow.

Note: Discussion open until December 1, 1957. Paper 1324 is part of the copyrighted Journal of the Air Transport Division of the American Society of Civil Engineers, Vol. 83, No. AT 1, July, 1957.

*Paper prepared for presentation at the Convention of the Society at Pittsburgh, Pa., October 16, 1956.

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INTRODUCTION

A snow runway was built on deep snow on the Greenland Ice Cap during the summer of 1955 by members of the 1st Engineer Arctic Task Force, Corps of Engineers, U.S. Army, commanded by Lt. Col. Elmer Clark and under the immediate supervision of Capt. John Napier, with Mr. Paul Beigbeder of the Engineer Research and Development Laboratories, Corps of Engineers, as project engineer. The author had the responsibility of testing the strip and was aided by members of the 1st Engineer Arctic Task Force, especially Pfc Frank Royse.

The snow for the runway was processed by modified pulvimixers using heat. Successful landings on the 200 x 10,000 ft strip were made by C-47, C-54, and C-124-type aircraft. This was the first time that heavy wheeled aircraft landed on a snow runway built on deep snow. The conclusion that the strip could support these aircraft and the decision to land the planes were based on the laboratory testing.

Considerable work has been done by the Canadian Defence Research Board and the Engineer Research and Development Laboratories, Corps of Engineers, on the making of snow runways. This report describes the methods and techniques used in testing a snow runway built on deep snow. It is not intended as a report on the operational aspects of making such a runway, nor as a critique on the techniques used. Also, it should be realized that this represents the beginning of a long-range program and that additional theoretical work and field work are still necessary.

Snow as a Construction Material

The making and testing of a snow runway differs in many respects from that of earthen or floating-ice-sheet runways. The Corps of Engineers has developed criteria for the economical construction of ground strips using various types of materials to safely support bombers of over 350,000 lb, or fighters with tire pressures of over 200 lb per sq in. On a high polar glacier, however, the subgrade, the base, and the wearing surface must all be made from snow.

Natural snow varies in density from 6 to 30 lb per cu ft and in grain size from 0.02 to 0.1 in. in diameter. Its strength is greatly affected by temperature, grain size, bonding, and age even for a given density. This is explained in greater detail in the appendix. Natural surface snow has very poor strength characteristics. It is not possible for ordinary wheeled vehicles to travel more than a few feet before becoming hopelessly mired. A tracked vehicle having a ground pressure of only 3 to 5 lb per sq in. may sink 1 to 5 in. in snow.

Because the strength of snow is affected by several factors, it is not easy to remold snow in the laboratory to duplicate the actual conditions; furthermore the presently available CBR in-place tests and curves are not adequate for determining the bearing capacity of a snow runway once it is made because of the differences in material already mentioned and the high plasticity of snow.

Test Procedure and Results

The testing procedure may be divided into three methods; (a) simple in-place testing, (b) the taking of undisturbed samples and testing them in a laboratory, and (c) large-scale testing. Procedures (a) and (b) require only two men and simple testing equipment. It is desirable that procedure (a) perhaps supplemented by (b) give sufficient information to predict the results of large-scale tests and the capabilities of a snow runway.

Simple In-place Testing

A large number of ram hardness readings were made systematically on the strip several times during the test period. The Rammsonde (see discussion by R. Haefeli[1]) is a simple penetrometer instrument which requires only one man to operate and another to take readings. A 36-in. profile may be obtained in about 5 minutes. A typical profile is shown in Fig. 1. The increase in values with time is due to the combined effect of age-hardening and increase in strength with decreasing temperature as the summer waned.

It may be noted in Fig. 1 that the 0-10 cm (0-4 in.) readings are considerably lower than the 10-15 cm (4-6 in.) readings, all in the same hard upper layer. This difference may be explained when it is realized that the Rammsonde head is a cone and the initial readings will be low until the full diameter of the cone is in the snow. The averaged readings from 0-10 cm are plotted against the averaged reading from 10-15 cm in Fig. 2. The slope of the straight line is 1/3, and since in many cases the surface layer is too thin to permit readings from 10-15 cm, it is recommended that the 0-10 cm Rammsonde readings be multiplied by 3 to give comparable values.

There is a time lag before the ambient temperature changes the snow temperature. There is also a decrease in amplitude of temperature variation with depth. As the actual temperature of the snow affects its strength, pits in the strip were dug and the temperature with depth obtained at various times.

Laboratory Testing

A laboratory was made by the simple expedient of digging a 6 x 8 x 8-ft. deep hole in the snow and covering it with a few 2 x 6-in. boards and a tarpaulin. The roof was soon covered by a foot of drifted snow. This provided an ample working space protected from the elements and at a temperature of about 14^{0}F. Undisturbed specimens for testing were obtained from the strip with a special auger. Vertical cores 3 in. in diameter and up to 34 in. long were obtained. The procedure used was to take several cores, note the position on the strip for each one, place them individually in cardboard tubes, and transport them to the snow laboratory. Here, each core was visually inspected and the depth of each layer and its structure noted. The core was then cut into sections with a maximum length of 10 in., the largest size useable in the specially-designed press. The diameter, length, and weight of each cut portion was measured in order to obtain the density with depth.

Density

The specific gravity and temperature of the snow before processing are shown in Fig. 3. It was noted that the processing caused a hard top layer of high density and strength; below it, the density decreased from that of the top layer to that of the virgin snow. A composite profile is shown in Fig. 4.

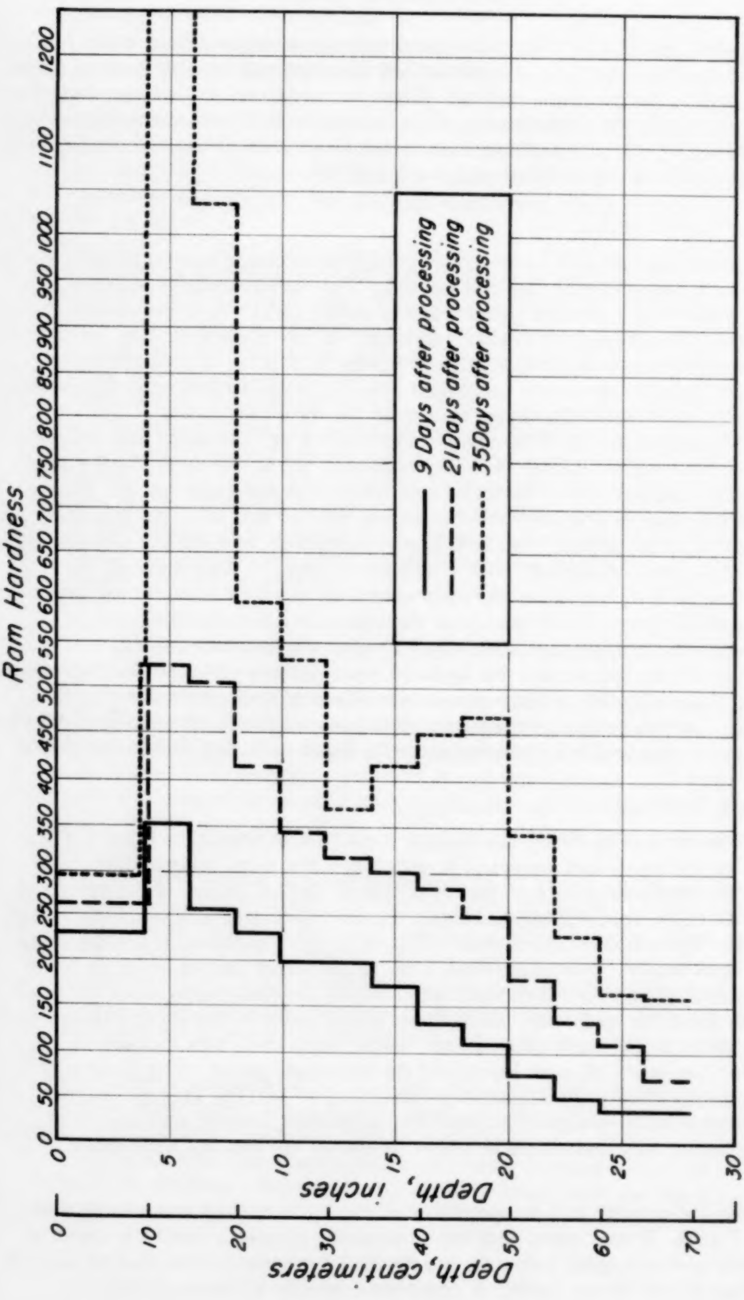

Fig. 1-RAM PROFILE WITH TIME.

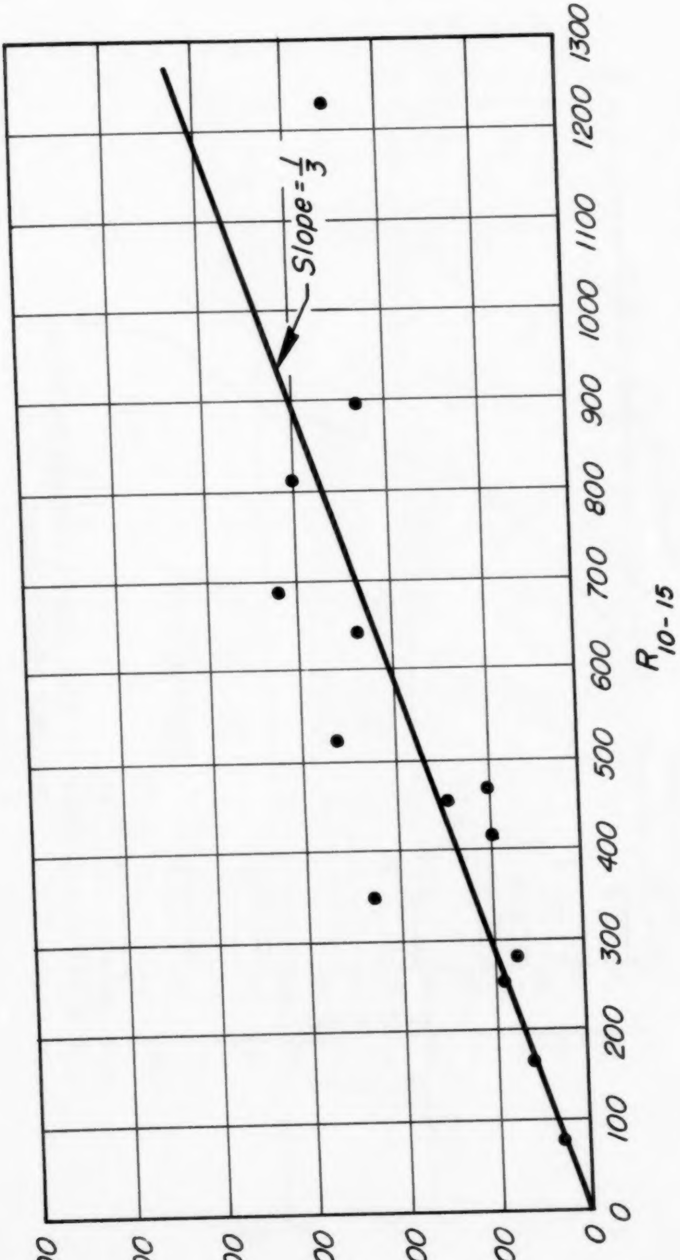

Fig.2 RAM READINGS FROM 0-10 CM vs READINGS FROM 10-15 CM

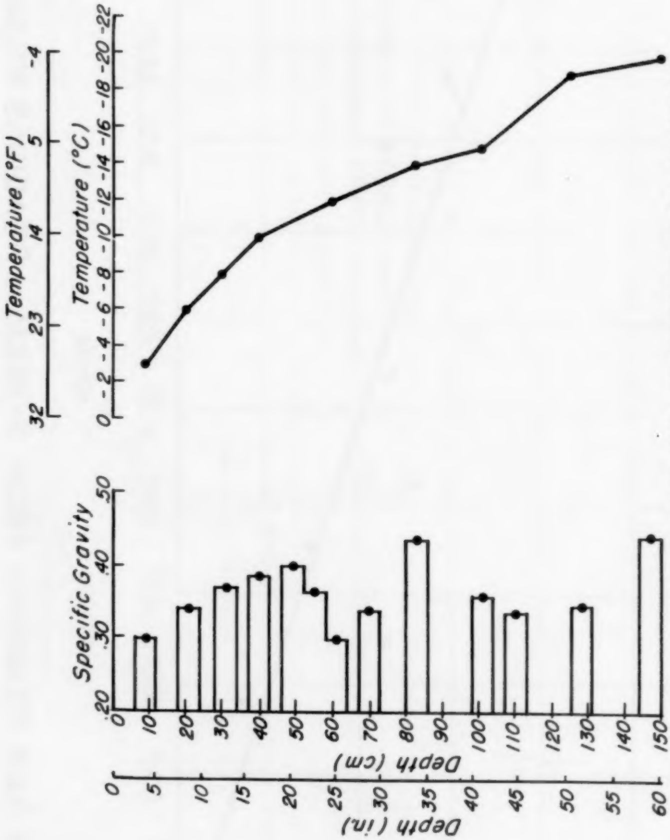

Fig. 3 SPECIFIC GRAVITY AND TEMPERATURE OF SNOW BEFORE PROCESSING

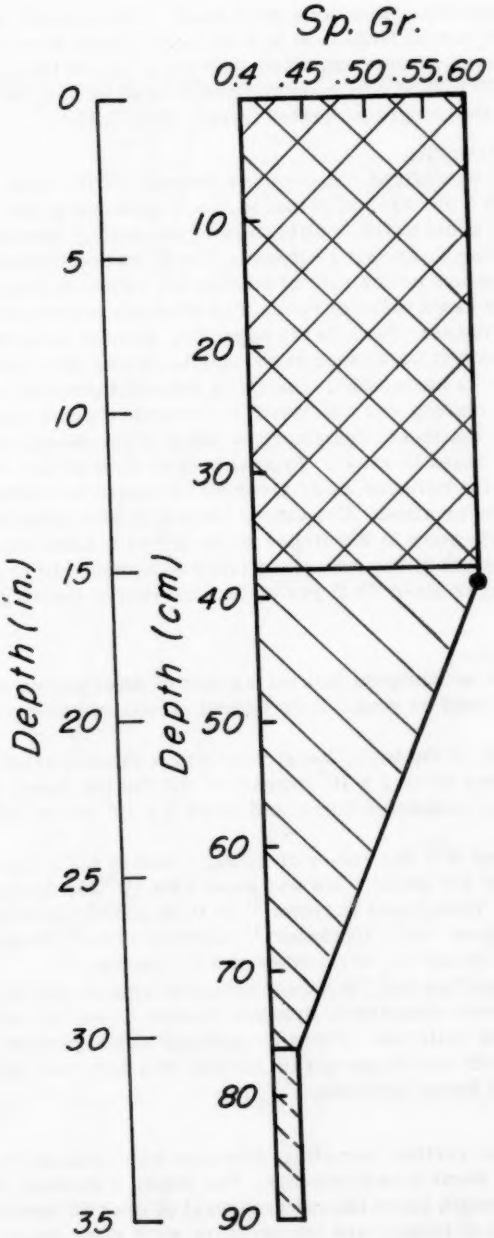

Fig. 4 COMPOSITE DENSITY PROFILE

Over 1000 density determinations were made. The specific gravity of the processed layer varied from 0.50 to 0.65, and in depth from 2 to 20 inches; the specific gravity of the compacted snow layer below the processed layer varied from 0.30 to 0.55 and in depth from 5 to 40 inches; the specific gravity of the virgin snow (subgrade) varied from 0.25 to 0.45.

Compressive Strength

The ultimate unconfined compressive strength of the vertical cores was determined with a mechanically-loaded, hand-operated press. The cores were allowed to come to the temperature of the testing laboratory; the average rate of loading was about 19 lb/sec. There was no deliberate attempt to vary the temperature or the rate of loading but rather to keep them about the same, noting the exact value of each. The strength values were all corrected to $+14^{0}$F in the manner shown in the appendix. Almost all of the virgin snow and the lower-density processed snow samples broke by a collapse of the snow structure in a horizontal plane and a large deformation accompanied the collapse. If the loading was continued, the pressure would again build up and cause another collapse and deformation. Most of the strong specimens of processed snow failed in shear. Typical breaks were of the cone type or at an angle across the cylinder axis. Over 400 ultimate unconfined compressive strengths were determined. The values varied considerably from 1 lb per sq in. for weak virgin snow to 200 lb per sq in. for very hard processed snow. The average strength of the processed layer was about 110 lb per sq in., for the compacted layer about 60 lb per sq in., and that of the virgin snow about 10 lb per sq in.

Stress-strain Ratio

The press was so designed that the amount of deformation of the sample as well as the load could be read. Four typical stress-strain curves are shown in Fig. 5.

Again, as in all of the tests, the stress/strain values varied considerably but the average was about 6×10^8 dynes/cm^2 for the top layer, 5×10^8 dynes/cm^2 for the compacted layer, and about 3×10^8 dynes/cm^2 for the virgin snow.

In SIPRE Report 4[(2)] the values of Young's moduli for ice are given as 1 to 5×10^{10} dynes/cm^2 for static tests and about 10×10^{10} for dynamic tests. Dynamic tests by Yamaji and Kuroiwa[(3)] on 0.54-density snow showed values of about 6×10^9 dynes/cm^2. Landauer[(4)] calculated from relaxation data a value of 1.6×10^9 dynes/cm^2 for a snow of 0.42 density.

It was to be expected that the values obtained from the strip testing would be smaller than those obtained by dynamic means, especially since we have a viscoelastic porous material. There is certainly some question as to whether values obtained from the stress-strain curves on a material like snow may properly be called Young's moduli.

Shear Strength

In addition to the vertical sampling, four pits were dug and horizontal samples taken for shear measurements. The depth, structure, density, and ultimate shear strength (zero lateral pressure) of over 90 specimens were obtained. The rate of loading and temperature were about the same as for the determination of the compressive strengths. Average values were about 60 lb per sq in. for the top layer, 40 for the intermediate layer, and about 10 for the virgin snow.

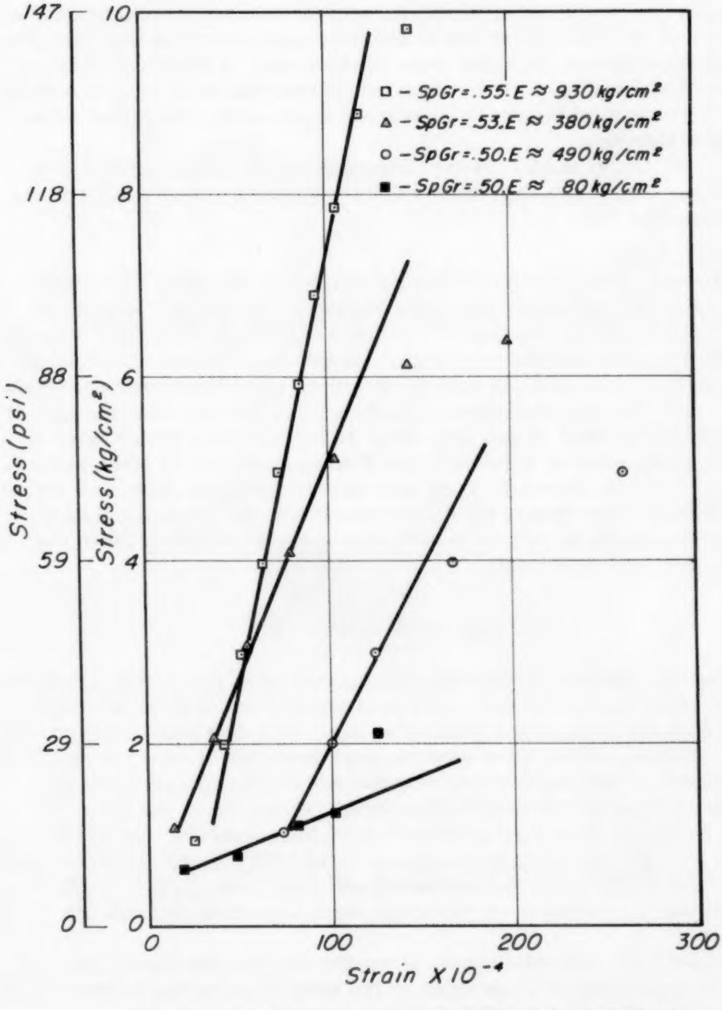

Fig. 5 TYPICAL STRESS- STRAIN CURVES.

Large-scale Testing

A four-wheeled rubber-tired Bros roller was pulled over the strip with varying loads to a maximum of 42,000 lb, with tire pressures at approximately 100 lb per sq in. The places where breakthroughs occurred were noted and studied. In some places the areas were reprocessed. A sketch of breakthroughs is shown in Fig. 6. It is important to note that in no case was there failure by a punching of the top layer into the layer below, but rather a disintegration of the snow.

Later, C-47, C-54, and C-124-type aircraft landed, taxied, and took off several times. The pilots said there were no unusual problems in the landings and take-offs.

Deflection Readings

Attempts were made to observe any deflections on the strip due to plate action, using a rod and transit that were available. The transit was set up and leveled about 100 ft from the rod resting on the snow. The "cat" operator drove the D-8 tractor and the Bros roller (42,000 lb), mounted on a skid, as close as possible to the rod and past it. Readings were taken before, at time of passage, and after they had passed. Although the rod was near the edge of both the D-8 and the skid, it was still about 10 ft from their center line. In some cases, deflections of $^1/100$ to $^1/200$ ft were observed; in other cases, no deflection could be detected. In no case did the observed deflection return to a zero reading. The size of the deflections are of the same order as the accuracy of the readings. It may therefore be considered that if there are deflections, they are very small.

DISCUSSION OF RESULTS

From the data obtained, a composite cross section of the runway shows it to consist of three main sections: (a) a hard top processed layer with high density and high strengths, (b) a compacted layer with decreasing density and strength with depth, and (c) a low density, weak subgrade of virgin snow. The maximum stresses with depth were computed for the various aircraft, approximating the tires as representing uniform circular loads and using the Boussinesq equation. Two main problems were then apparent: (a) that the top layer be of sufficient strength to support tires with a given pressure, and (b) that the total thickness of the processed and compacted layer be sufficiently great that the stresses on the virgin layer are small and will not cause collapse.

It is realized that confined ultimate strengths (as actually exist in the runway) would be higher than that obtained by the laboratory testing of unconfined samples. This was used as a safety factor.

Breakthroughs occurred where the pulvimixers had not sufficiently processed the snow or where (even though the density was high) poor cohesion developed in the snow because large icy clumps had formed. The compressive strength values where breakthroughs occurred compared very well with that of the testing vehicle.

Fig. 7 shows a plot of the ram hardness versus the compressive strength, with each point representing a large number of tests. The straight line, R, was computed by means of least square and if σ is in psi then

$$\sigma = 0.57\ R - 32.5 \qquad (1)$$

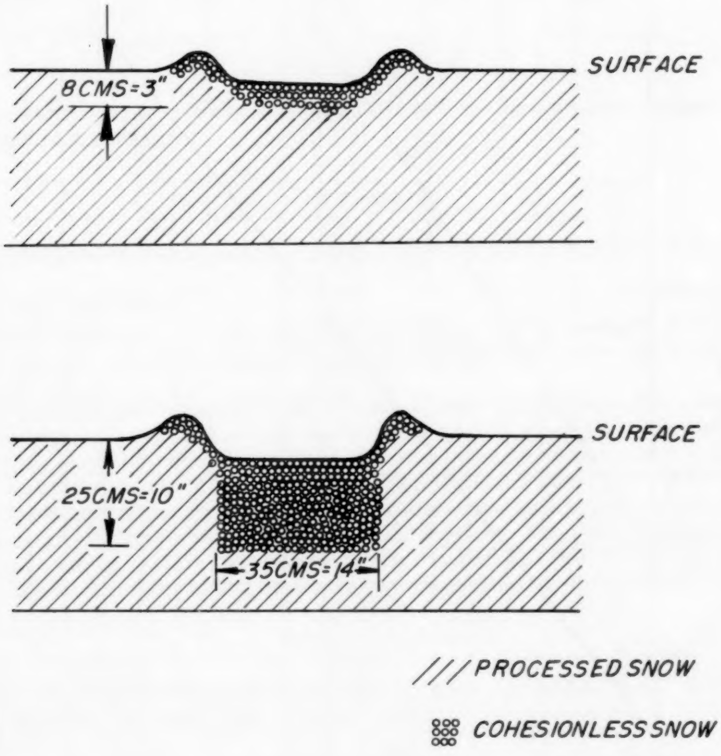

Fig. 6 SKETCH OF BREAKTHROUGHS

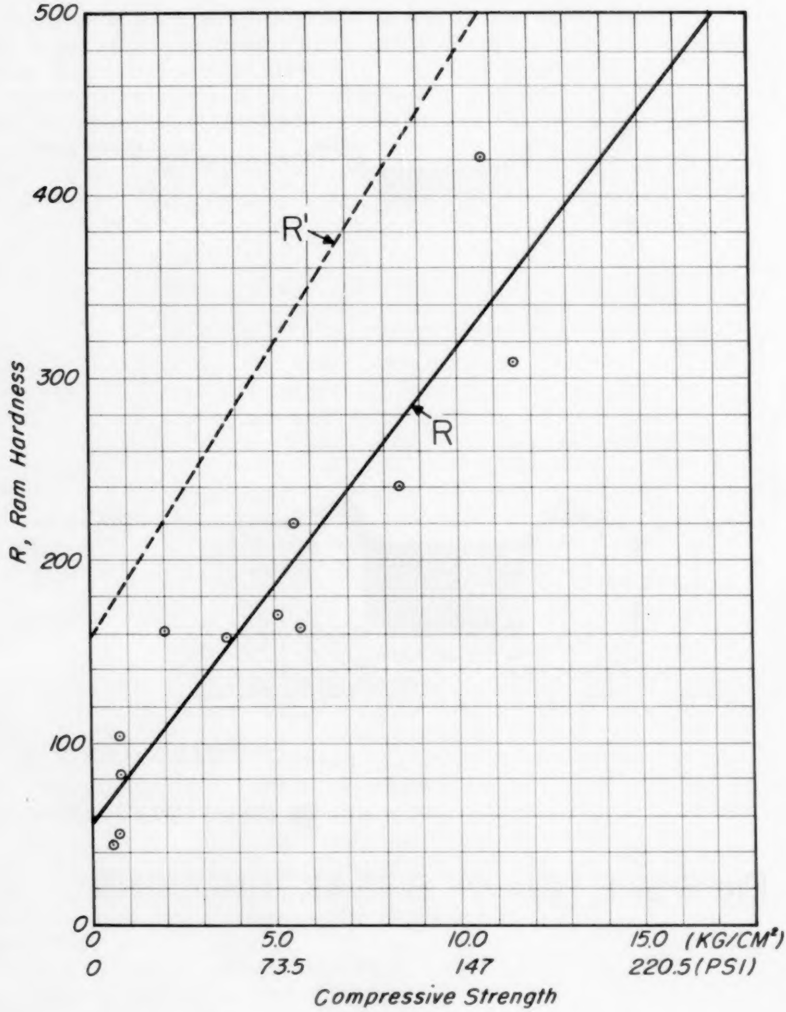

Fig. 7 RAM HARDNESS vs COMPRESSIVE STRENGTH.

For a ram hardness value of 57 or less there is no compressive strength. This is to be expected as an entirely cohesionless material would give a ram reading and the strength values given here are for the unconfined case.

A plot of known ram hardness values for a processed surface that supported or failed under various tire pressures is shown in Fig. 8. The straight line (also shown in Fig. 7 as R') may be expressed by an empirical equation as

$$\sigma\,(\text{psi}) = \frac{R}{2} - 80 \tag{2}$$

For operational purposes, it is suggested that the Rammsonde be used as a simple test instrument.

APPENDIX

Effects of Temperature and Age-hardening on the Strength of Snow

Temperature Effect

Quantitative data on the effect of temperature on the strength of snow is limited, although there is general agreement that "the colder the snow is, the stronger it is."

Bucher[5] performed a series of experiments to determine the effect of grain size, density, and temperature on the tensile strength of low-density snows. Fuchs[6] obtained a series of shear strength vs temperature curves for screened snows of high densities. The Russians also have a curve on hardness vs temperature with hardness measured by a surface cone penetrometer.[7] Butkovich[8] in his work on snow-ice found the crushing strength to have a temperature dependence similar to that obtained by Fuchs.

Almost all of the above data may be represented by the equation

$$\log \frac{S_2}{S_1} = 0.16 \log \frac{T_2}{T_1} \tag{A1}$$

where S_1 = is the strength at $T_1{}^{\circ}C$ and S_2 is the strength at $T_2{}^{\circ}C$. It is easier to use this in a graph form as shown in Figure A1 by a series of parallel lines.

Example: If the strengh at $-5^{\circ}C$ ($23^{\circ}F$) was 3.6, what is the strength at $-30^{\circ}C$($-22^{\circ}F$). Draw a line parallel to those shown and passing through 3.6 at $-5^{\circ}C$. The answer then is 4.8 at $-30^{\circ}C$, in this case a 1/3 increase in strength. Or, if a slide rule is handy: $\log S_2 - \log 3.6 = 0.16 \log \frac{30}{5}$.

It was also pointed out by Bucher that the strength of a fine-grained snow is much more temperature-dependent than that of a coarse-grained snow. This is shown in Figure A2.

Age-hardening

A number of people[9] have suggested reasons for a given snow becoming harder with time, and the phenomenon has been observed by many people in the field. Nevertheless, there is very little quantitative information on the rate of age-hardening with time and as a function of temperature.

Although the term "hardness" or "hardening" is usually thought of in terms of resistance or increase of resistance to penetration, in snow it has come to

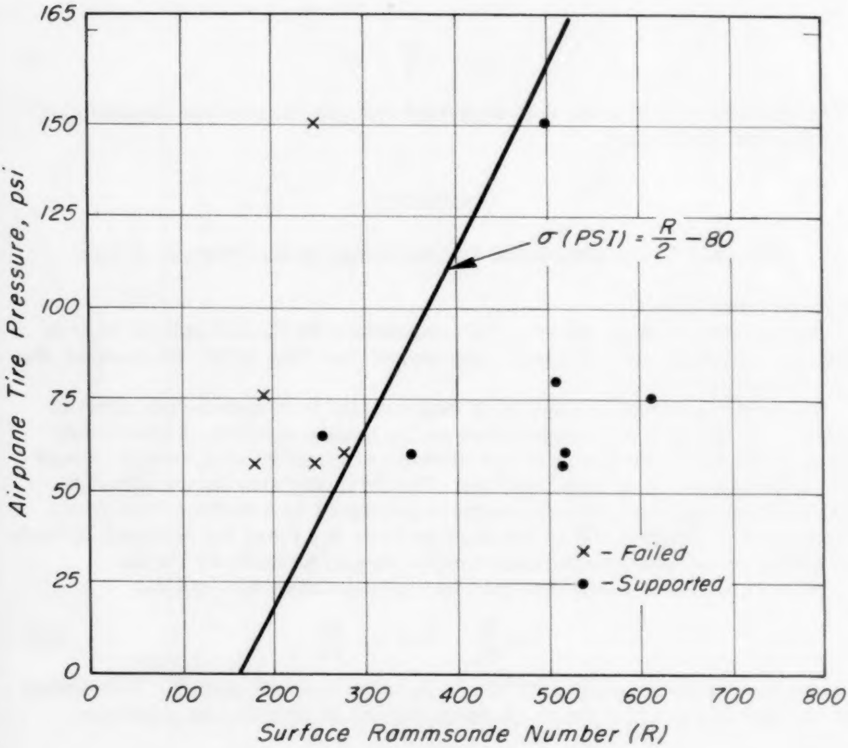

Fig. 8 TIRE PRESSURE vs RAMMSONDE NUMBER.

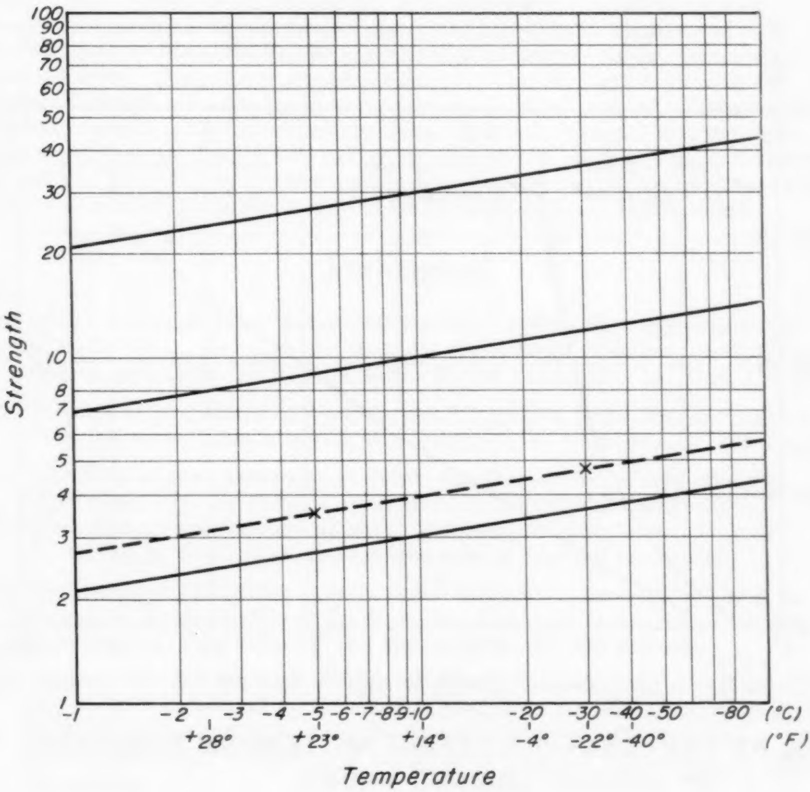

Fig. AI STRENGTH vs TEMPERATURE.

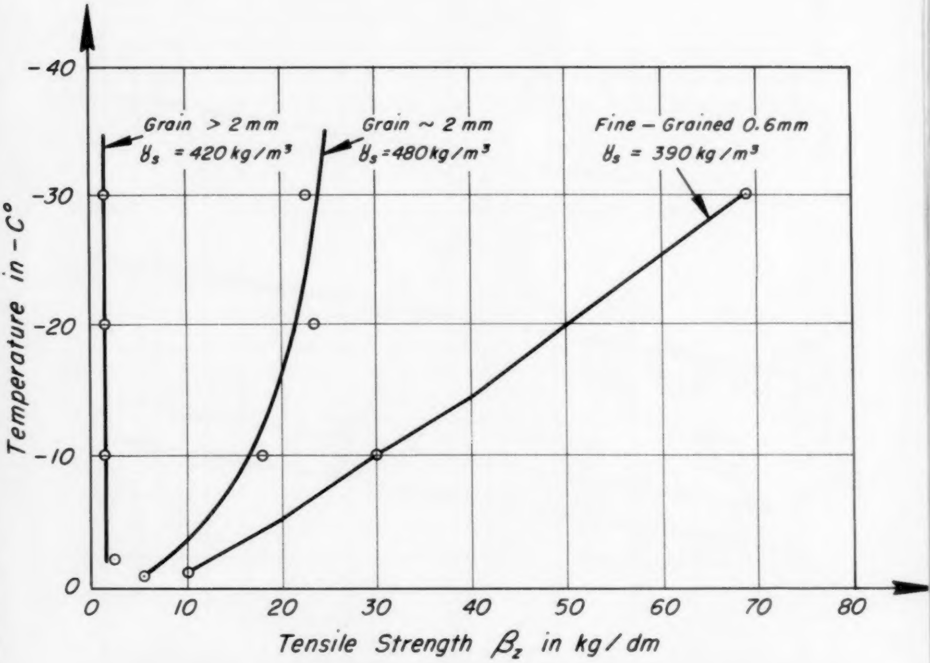

Fig. A2 TEMPERATURE EFFECT ON TENSILE STRENGTH OF VARIOUS GRAINED SNOWS.

indicate the corresponding increase in strength as well. The author performed a series of investigations in the SIPRE laboratory of age-hardening. A typical curve for a screened snow compacted to a density of 0.60 and allowed to harden at a temperature of -5°C (22°F) is shown in Figure A3. Fuchs(10) also ran a series of tests on screened snow, but used a direct shear test to measure the hardening. His curves are similar to the one shown in Figure A3, but he found a maximum increase in hardness at -4°C (25°F). Fuchs also noted that fine-grained snow became harder than coarse-grained snow. The ratio of strength increase, i.e., strength at time of compaction/strength several days later, is shown in Figure A4, which represents the average of the SIPRE laboratory tests. It should be noted that the case where the snow originally was wet is not considered. A good rule of thumb is to allow at least 3 days of hardening at moderate temperatures and about 4 to 5 days at low temperatures before strength tests or heavy traffic tests.

REFERENCES

1. "Der Schnee und seihe Metamorphose (Snow and its Metamorphism)," by H. Bader et al., Beitrage zur Geologie der Schweiz, Geotechnische Serie, Hydrologie, Lieferung 3, Bern 1939. SIPRE Translation 14, 1954, Ch. II.
2. "Review of Properties of Snow and Ice," Report 4, Snow, Ice, and Permafrost Research Establishment, U.S. Army, Corps of Engineers, 156 pages.
3. "Shindoho ni yoru sekisetsu no dansei oyobi nensei no kenkyu (Study of Elastic and Viscous Properties of Snow by the Vibration Method)" by Kenji Yamaji and Daisuke Kuroiwa, Teionkagaku (Low Temp. Sci.), Ser. A, vol. 13, p. 49-57 (Text in Japanese with an English summary).
4. "Stress-Strain Relations in Snow under Uniaxial Compression," by J. K. Landauer, Research Paper 12, Snow, Ice, and Permafrost Research Establishment, U.S. Army, Corps of Engineers, 1955, 9 pages.
5. "Beitrag zur den theoretischen Grundlagen des Lawinenverbaus (Contribution to the Theoretical Foundations of Avalanche Defense Construction)," by Edwin Bucher, Beitrage zur Geologie der Schweiz, Geotechnixche Serie, Hydrologie, Lieferung 6, Bern, 1948. SIPRE Translation 8, 1956, 109 pages.
6. "Die Scherfestigkeit von Schnee und Eis in Abhangigkeit von der Temperatur (Shear Strength of Snow and Ice as a Function of Temperature)," Veroffentl. Museum Ferdinandeum Innsbruck, vol, 26, 1946, p. 101-195.
7. "Sukhoputnyi Transport lesa (Overland Hauling of Logs,)" by V. V. Buvert, et al., Moscow: Goslesbumizdat.
8. "Crushing Strength of Lake Ice," by T. R. Butkovich, Research Paper 15, Snow, Ice, and Permafrost Research Establishment, Corps of Engineers, U.S. Army, 1955, 5 pages.
9. Bader, et al., op cit.

"Snow Compaction," by Andrew Taylor, Report 13, Snow, Ice, and Permafrost Research Establishment, 1953, 64 pages.

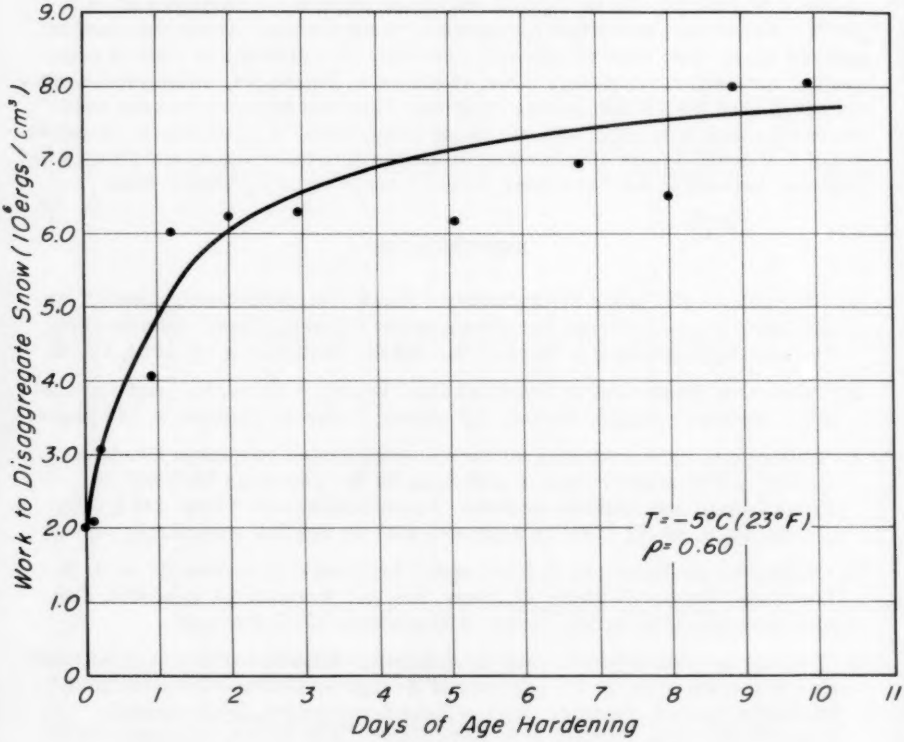

Fig. A3 WORK TO DISAGGREGATE SNOW vs DAYS OF AGE HARDENING

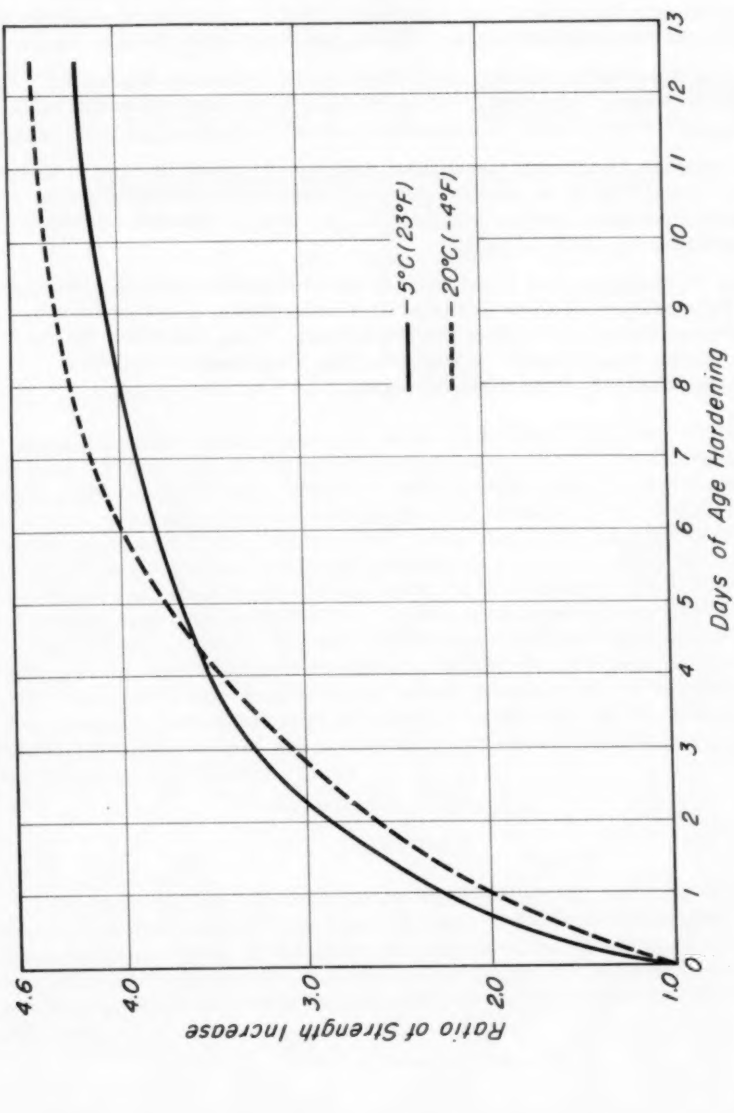

Fig. A4 RATIO OF STRENGTH INCREASE vs DAYS OF AGE HARDENING

"Izmenenie mekhanicheskikh svoistv snegovogo pokrova vo vremeni (Change of Mechanical Properties of the Snow Cover as a Result of Time)," by I. V. Kragel'skii, and A. A. Shakhov, in "Physical and Mechanical Properties of Snow and Their Application in the Construction of Airfields and Roads "Moscow-Leningrad: Akademiia Nauk SSSR, 1945, p. 10-13.

"Schnee als kristallines Aggregat (Snow as a Crystalline Aggregate)," by M. De Quervain, Experentia, vol. 1, 1945. SIPRE Translation 21, 1954, 7 pages.

"Fizicheskie protesessy v snegovom pokrove (Physical Processes in a Snow Cover)," by A. A. Shakov, Izvestiia Akademii Nauk SSSR, Seria geograficheskaia i geofizicheskaia, vol. 12, 1948, p. 239-248. SIPRE Translation 15, 1952, 17 pages.

10. "Uber Verfestigung von Lockerschnee durch Metamorphose in Abhangigkeit von Temperatur, Zeit und Korngestalt (Consolidation of Loose Snow by Metamorphism as a Function of Temperature, Time, and Grain Form)," by A. Fuchs, Versuchber. 2, Ber. No. 241, Forschungsanstalt Graf Zeppelin, Stuttgart-Ruit, 1942, 16 pages.

Journal of the
AIR TRANSPORT DIVISION
Proceedings of the American Society of Civil Engineers

AIRCRAFT OPERATIONS ON FLOATING ICE SHEETS*

S. Russell Stearns,** A.M. ASCE
(Proc. Paper 1325)

FOREWORD

Symposium on Cold Regions Air-Transport Problems

Polar air routes and air bases north of the Arctic Circle have added a new and exciting dimension to the already scintillating field of air transport. Developments on this frontier have been made possible through the cooperative efforts of operating personnel and engineering technologists. In the Symposium, presented at the October 1956 Convention of the Society (of which this paper is a part), the part played by workers in an exacting field is dramatically written in statements of problem areas, in the results of their research, and in their hopes and anticipation of future application of their findings.

The five papers (Proc. Papers 1323 through 1327) and attendant discussions represent the most advanced knowledge available on cold regions air transport. The papers have been selected to take advantage of the special abilities of the authors, each of whom is an emminent authority, and to indicate for readers the opportunities and problems in this area of military and commercial transport significance.

ABSTRACT

This paper outlines the fundamental relations of load and support of a floating ice sheet and extends these concepts to problems of aircraft operations on this medium. The failure mechanism of ice sheets is explained and limiting load conditions for various failure-stages are indicated. Ice-survey procedure and the effects of variable factors on load capability are carefully set forth.

Note: Discussion open until December 1, 1957. Paper 1325 is part of the copyrighted Journal of the Air Transport Division of the American Society of Civil Engineers, Vol. 83, No. AT 1, July, 1957.

*Paper prepared for presentation at the Convention of the Society at Pittsburgh, Pa., October 16, 1956.

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INTRODUCTION

Throughout history one finds continuous reference to the use of bodies of ice—frozen rivers, lakes, oceans—as avenues of transportation where otherwise their objectives would be isolated. In recent years, considerable publicity has been given to the development of tractor supply trains traveling the frozen waters of the Arctic, to the development of air supply routes with termini on floating ice airfields, to the Dewline and Antarctic construction and supply operations based on ice landings, and to the spectacular use of ice routes by the Russian Army for personnel and supply movement during World War II. At the start of World War II the Russian experience was sufficient to permit them to move loads over fairly thin ice. As a result of this knowledge of the bearing capacity of ice plates, obtained from research and actual field tests and maneuvers, they were able to keep supply lines open in several most critical situations.

Also throughout history one finds mention of a number of scientists and engineers who have struggled with the mechanical theory and action of a floating plate, in our case, an ice sheet. H. Hertz(1) in 1884 reported on loads applied to "swimming" ice. Dean Westergaard(2) wrote about plates on fluid foundations in 1923, 1926, and earlier. Others include Nadai,(4) Schleicher,(5) and Assur.(6) In recent years the efforts of a number of research establishments in the United States, Canada, Japan, and Russia have been focused on this problem. Also, information has been accumulating as more and more use is made of floating ice facilities. For example: Squadron Leader Scott Alexander, RCAF, through a decade of light- and medium-weight aircraft supply operations in the Canadian Arctic islands, had, by 1955, developed a sound working knowledge for operations on ice.

However, the establishment of a complete set of rules, or operating limits, for airfields on ice has not been completed. Additional information about the basic properties of ice, and the action of ice sheets under varying load and climatic conditions is necessary.

This paper will briefly review the mechanical action of a floating ice sheet under load, and the relationship of various properties of the ice to this action. It will become evident that the result is empirical and factors of safety are required. Finally, a recommended approach to the selection of a location, and to operational procedure will be given.

Fundamental Relations

A floating ice sheet is understood to be the ice cover of a body of water, floating in the water surface, and not ground-fast at any point. No air space should exist between the ice and water. It is not a chunk, or raft, of ice like the Arctic ice islands. It deflects under load as a plate rather than submerging rapidly as a cake of soap. This is the plate which H. Hertz studied in 1884, and Dean Westergaard applied the same concept, with approximations, to a concrete slab supported by subgrade reaction, k. The loaded ice sheet gives us the true picture of resistance to bending of an elastic-plastic plate on an elastic foundation, elastic under moving loads and initially under a static load, but plastic under parked, or long term loads. The plastic aspects cannot be treated very well theoretically at present.

The well-known deflection curve for a point load which results is a function of:

E = modulus of elasticity, Young's modulus
μ = Poisson's ratio
h = ice thickness
k = fluid pressure per unit of area, per unit of deflection
P = magnitude of load
a = radius of a circle over the area of which P is assumed to be distributed uniformly
the shape of the loaded area

Interior loading, or at an appreciable distance from an edge, is assumed. For computing the shape of the deflected surface in the general case the shape of the loaded surface and the distribution of load on it have to be known. For a circular load, the radius is used.

The late Dean H. M. Westergaard provided the following formula for the deflection of the sheet.(2)

$\delta_o = \frac{P}{8kL^2}$ where δ_o is the deflection under the load, P, and

$$L^4 = \frac{Eh^3}{12(1-\mu^2)k}$$

Dean Westergaard later(3) discussed the effect of the area of contact between load and plate, and introduced a modifying factor which is a function of $(\frac{a}{L})$. Then

$\delta_o = \frac{P}{8kL^2} F(\frac{a}{L})$. The $F(\frac{a}{L})$ is almost equal to unity even when (a) approaches the value of (L).

$\delta_o = \frac{P}{8kL^2}$ can be used for practical purposes.

The parameter, L, called the radius of relative stiffness, or action radius,(8) is of major interest to us since it provides a scale for measuring the shape of the deflection. Examination of the curve in Fig. 1 shows that the lateral extent of the deflection curve is not large. At 3.9 L the deflection changes from downward to upward. The upward hump becomes maximum at about 5 L and disappears 7 L. Anyone who has skated on thin ice has vivid recollections of this dish-shape.

It is important to know the extent of the curve which will develop under the expected conditions. For example, in test work one should use an ice sheet larger in lateral dimensions than 10 L, and preferably larger than 14 L, to avoid side or edge influence. In actual operations on ice sheets one should space loads, such as vehicles, planes, or supply piles, far enough apart to avoid superimposing the depression under one load on the depression under another. A distance of 4 L to 5 L is reasonably safe.

Since L is a function of E, μ, k, and h, (but not load intensity, P) a few words about these factors are necessary. Ice is not a common or well-known material of engineering as are steel and concrete, for example; it is much more similar to soil with its variable properties. The modulus of elasticity of ice varies with temperature, rate of loading, structure, and salinity(7); and additional data must be obtained from tests, both laboratory and field. Poisson's ratio can be considered a constant at 0.33. The subgrade reaction,

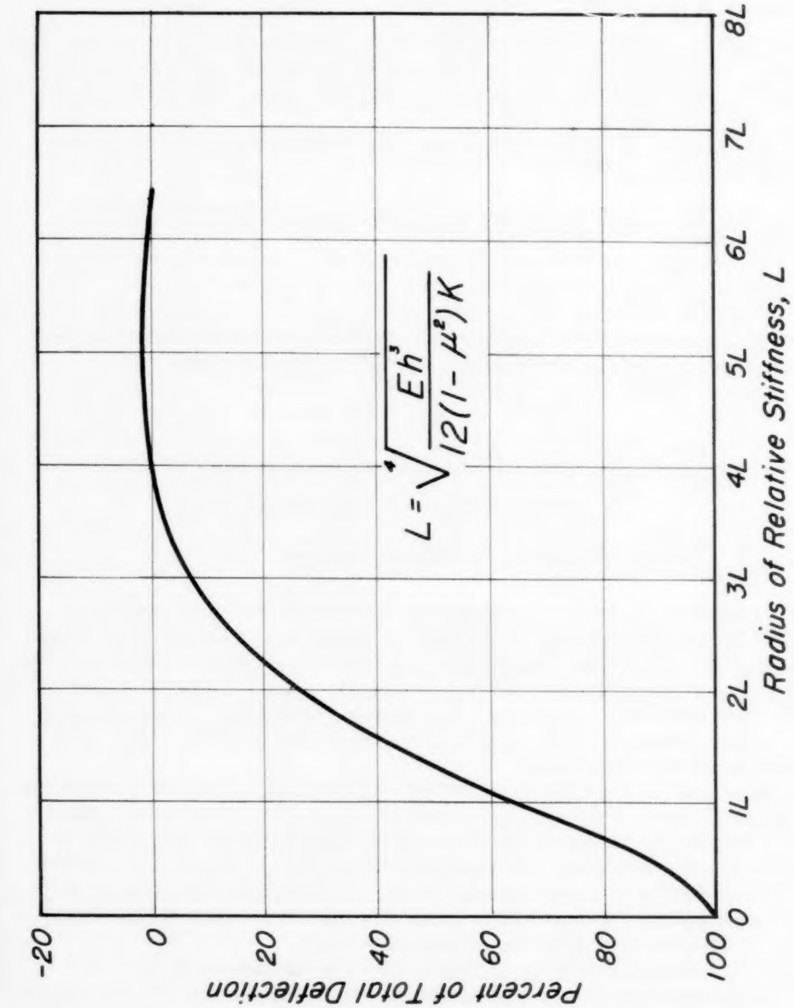

Fig. I ICE DEFLECTION vs RADIUS OF RELATIVE STIFFNESS

k, is equal to the density of the fluid and is thus known. Therefore, major variations of L, and of the magnitude of the deflection, depend primarily upon the ice thickness, and secondarily upon the effect of ice type, temperature, and rate of loading as they change the modulus of elasticity.

Fig. 2 shows for fresh water, and for sea ice, this relation between ice thickness and a 5 L radius assuming average ice conditions and slowly-moving loads.

Large scale field tests performed by the personnel of the Snow, Ice, and Permafrost Research Establishment, Corps of Engineers, US Army (SIPRE) have verified very nicely the theoretical relations just discussed. Observed deflections agree well with the curves derived by Hertz and Westergaard as adapted for ice. This correlation is a most striking example of agreement between theoretical development for formulas and physical tests.

These formulas are based on elastic action, and the stresses resulting from resistance to bending can be computed only within the proportional range. The dish-like deflection of the ice sheet causes primary flexural stresses, with resulting tension cracks, in the bottom surface of the sheet at the center. One can compute with confidence the load which will cause this first crack if the physical properties of the ice are known. But after this crack, the elastic theory no longer applies, and the problem becomes subject to empirical solution.

It is most important to understand at this point that the first crack does not signify that the maximum safe load has been exceeded, or that complete failure of the ice will follow immediately. If this were the case, loading of ice sheets would be so limited that many operations would not be feasible. It is true that if the load remains in the same spot, complete failure will probably occur in time, due to progressive creep. This creep, accompanied by appreciable sagging, cannot be analyzed by the elastic methods, of course. Quick loading beyond the first crack, or slow loading with resulting plastic deformation, must be studied by use of laboratory tests or models, and full-scale field tests.

The SIPRE field tests have shown that loads causing final failure are greater than the first-crack loading. Therefore, the load at the time of the first cracking can be used for short periods with controls without probable breakthrough.

The deflection curve in Fig. 1 shows bottom tension in the center and top tension at some distance from the center. It follows that the first cracks, starting in the bottom surface, are radial from the center and cut a series of pie-shaped pieces. The second major cracking, accompanied by a definite slump of the surface, occurs when the tensile stresses in the top surface exceed the ice strength; then a circumferential crack develops suddenly, cutting off the triangular pieces.

Nevertheless, the load will still be supported, particularly if the radius of the loaded area, a, is appreciable so that the triangular wedges are loaded as beams away from their points. In this case, final breakthrough will occur when these beams fail. By this time, the whole deflected area will have sagged and collapsed to a large degree.

Empirical Relations

It is necessary to develop an empirical approach to the prediction of safe bearing capacities of floating ice sheets by starting with the theoretical

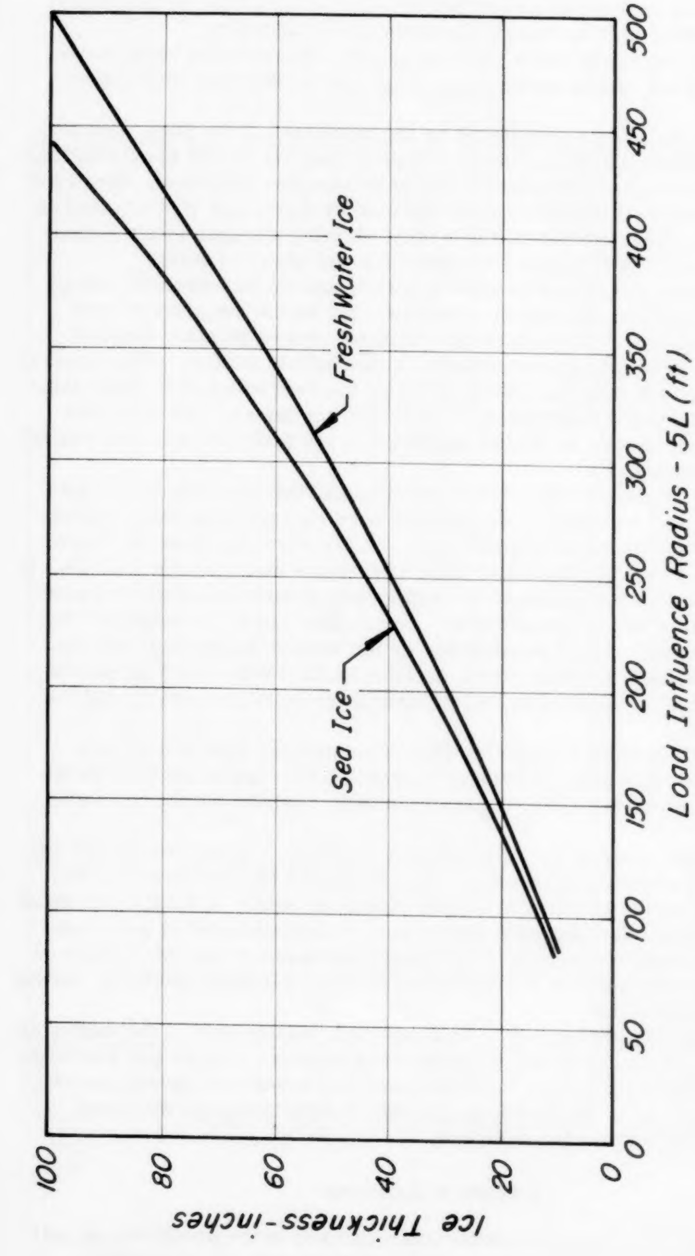

Fig. 2 RELATIONSHIP BETWEEN ICE THICKNESS AND LOAD INFLUENCE RADIUS FOR AVERAGE ICE CONDITIONS AND SLOWLY MOVING LOADS.

Photo No. 1—Airlift to Polar Regions.
Unloading C-124 aircraft on an ice airfield.

relationships given previously for the first crack. To this basic equation factors must be added to introduce the tensile strength of top and bottom layers, the type of ice—homogeneous or stratified, fresh or salt,—the rate of loading, the ice temperature, and the type of risk involved. Use of such modifying parameters would allow one to predict how far beyond the safe first crack one can go with maximum loading before complete breakthrough occurs.

Values for these variables can be obtained by means of "on the spot" tests, or by just assuming average or safe values. "On the spot" tests require the delivery of a party with equipment to the location, a procedure which, although time consuming, difficult, and perhaps risky, is recommended in most cases. In this way a complete study of the location and ice conditions can be made. On the other hand, to assume values for the thickness, structure, and strength of the ice requires considerable experience, and is at best rough. Knowledge of the local climate and hydrography under which the ice was formed is necessary. This information is obtained only through observations carried out over appreciable lengths of time in the areas being considered.

Let us consider for a moment each of the major factors mentioned and how its working value can best be determined. The need for continued study of the relationships between the modulus of elasticity and ice type, temperature, and rate of loading was mentioned earlier. However, enough information for fresh-water ice is now available in the literature of several countries to enable us to assume a reasonably safe value for Young's modulus; for example, SIPRE Report No. 4.[7] Similar information is lacking for salt-water ice. We must for the present introduce factors of safety to protect against this ignorance.

The magnitude and type of load which is anticipated, and the shape and

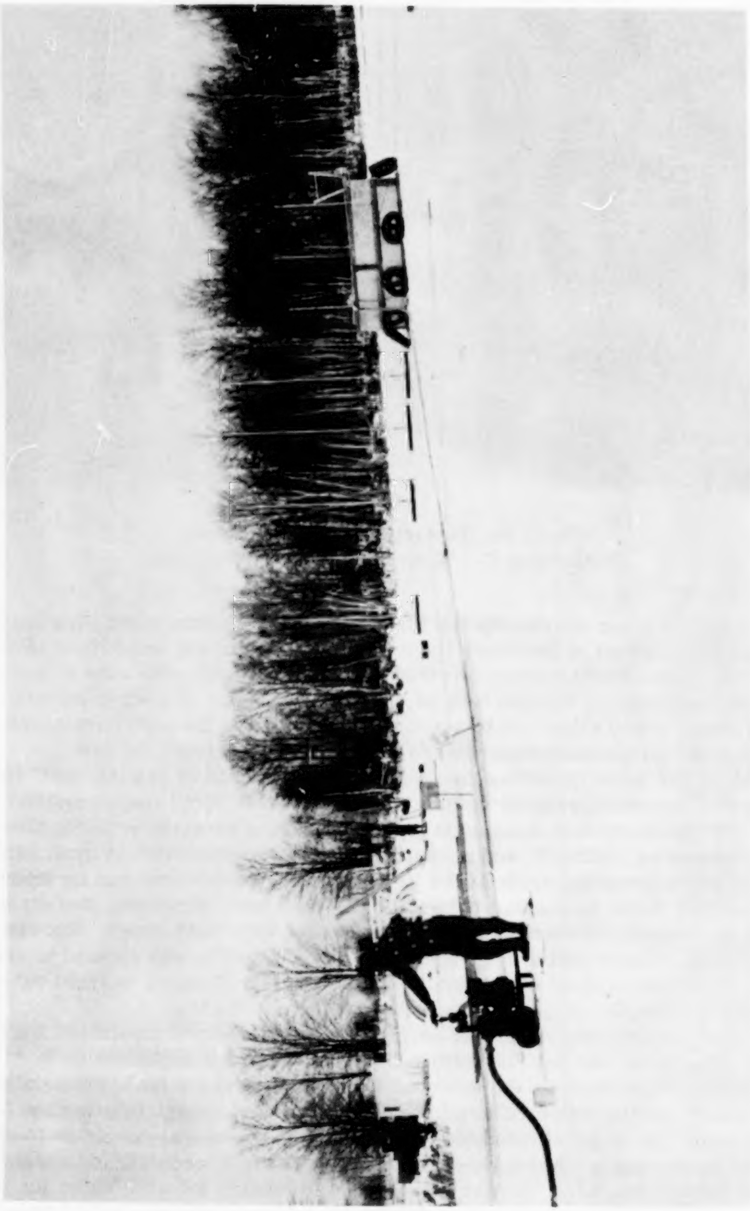

Photo No. 2–Tank loading test. Pump in foreground, level and deflection rods in background.

Photo No. 3—Ice broken through by tank load.

Photo No. 4—Typical circular breakthrough showing wedge-shaped ice blocks.

size of its contact area, must be determined. For example, under similar conditions, a C-47 aircraft on wheels requires greater ice thickness than a C-47 on skis.

For ice thickness an actual determination in the field is best. A survey of a proposed strip can be accomplished quickly by using a hand auger. SIPRE has developed and made available an auger for this purpose. The survey party must be careful to obtain the actual thickness of sound ice, and not be misled into including slush ice often found.

Estimates of ice thickness can be made based on records of air temperature in degree days below freezing, and on snow cover. Such estimates give only average values for ice thickness, and, if used to determine the suitability of a particular location for a landing, a generous factor of safety is in order. For example, it is often necessary to predict an ice thickness prior to the landing of an ice survey team. It is wise, in such a case, to apply a factor of safety when comparing the thickness estimated from temperature records to the thickness required for the particular plane to be used on the survey.

At least one hole should be made large enough so that the ice structure can be examined. Snow or slush ice often forms on top of, or layered with, dense ice and the total thickness of such a stratified system must be reduced to account for the presence of this weaker material. A safe approximation is to use one-half of the thickness of snow ice as effective. This is

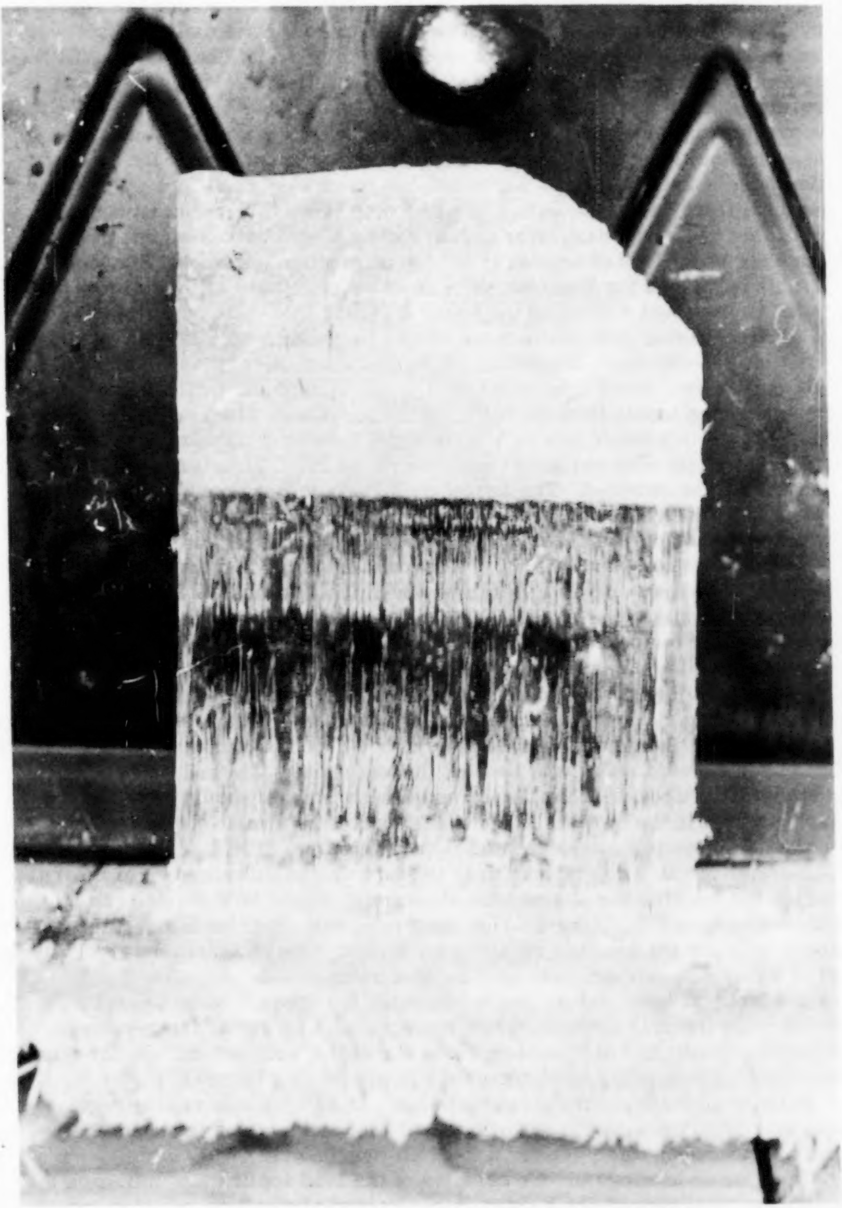

Photo No. 5—Layered system, snow ice over clear ice.

conservative in many cases for dense snow ice approaches sound ice in strength.

In considering the deflection of the ice sheet under load and the resulting overstressing of bottom and top layers, the need for a correlation between values of the flexural strength of the ice and the actual bearing capacity was apparent. The best test here is, of course, a full-scale landing, but this is rarely feasible. In its place a large-scale, static-load test, such as the tank apparatus shown earlier, can be substituted. This is possible, under research conditions, but is not generally a reasonable approach for an operational ice survey. Trained personnel can more easily and quickly perform flexural tests on beams, either in place or removed, if sufficient time is available. In-place cantilever beams can be loaded both down and up to simulate conditions of tension in the top and bottom surfaces. Fig. 3 shows a simple apparatus for this test. The modulus of rupture of the beam is computed in the usual way using the flexural theory.

The cantilever test, while much easier to perform than the full-scale load test, is, nevertheless, demanding in its execution, particularly under cold and wet conditions. More convenient still is the simple and familiar beam test performed on small samples cut from the ice sheet. Many tests can be performed in this manner in a relatively short time, and indications of the variation of strength with changing temperature, salinity, structure, and rate of loading can be obtained. The influence of these factors must not be underestimated. It is most important, in all these tests, to develop a correlation with the actual, in-situ bending strengths and bearing capacities.

Already discussed as the most important factor, and most readily determined, is the ice thickness. However, even ice thickness is not stable over periods of temperature change. Sea ice continues to grow as long as the average daily temperature is below approximately 10°F. The actual figure depends upon the salinity, conductivity of the ice, and snow cover. Conversely, when the temperature goes above 10°F the ice starts to decrease in thickness. This decrease might occur at the bottom where the weaker ice becomes liquid, and the harder ice immediately above becomes weaker. Also the whole ice cover tends to soften and become discontinuous. The reduction in thickness is not noticeable from the top and measurements should be taken regularly. Later in the spring the ice melts or softens also from the top.

The temperature also affects the strength of ice. The flexural strength of salt-water ice at temperatures near the freezing point becomes very low although the ice still has appreciable thickness. Below 10°F the ice can be considered to have full strength under most conditions, but for temperatures above 10°F ice thicknesses required for loading must be increased gradually up to 50 percent, and operations may become risky.

The critical temperature for fresh-water ice appears to be around 24°F at which point flexural strength starts to decrease with rising temperatures. For some conditions of snow cover and structure, and particularly for thick ice sheets, thickness may decrease for temperatures above 24°F.

Salinity also affects the strength of ice. At 22°F, and assuming regular (not marginal) operation, approximately 10 in. more of sea ice would be required than fresh-water ice for a C-47 on wheels.

The rate of loading, and the duration of the load application, influence the thickness requirement for a given load. Parked aircraft or vehicles, or stockpiles of equipment and supplies, or even plowed up snow piles will cause plastic deflection of the ice sheet and an appreciable sagging may be noticed.

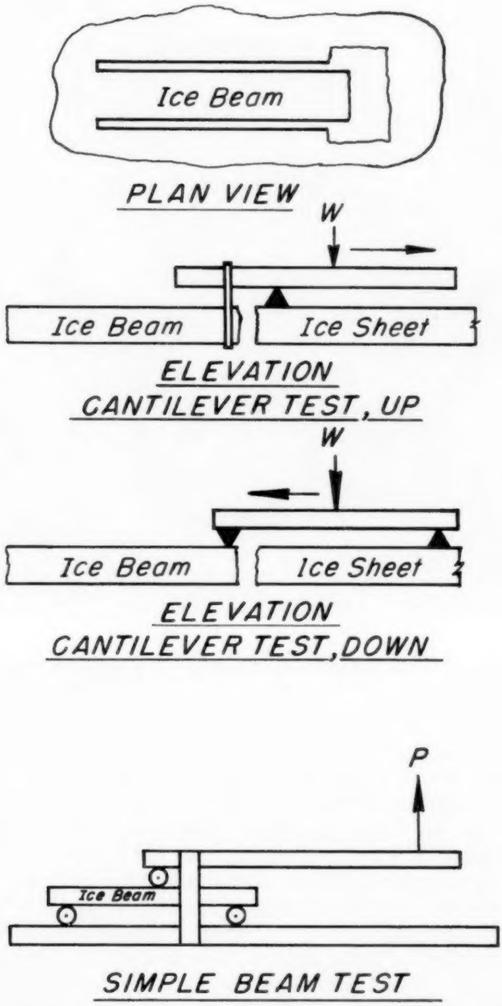

Fig. 3 ICE BEAM TESTING ARRANGEMENTS

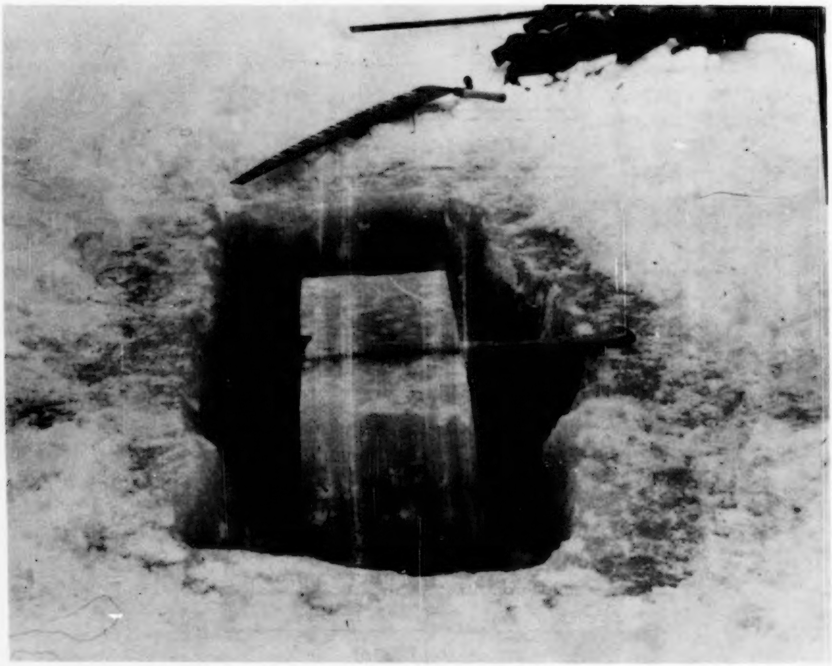

Photo No. 6—Sea ice block ready for sawing into beams for flexure tests.

If the load is not moved, the sag will increase progressively until a swamping of the area or even a breakthrough of the load may occur.

Finally, resonance waves developed in the ice sheet by moving loads must be taken into account. Critical velocities of moving loads depend upon the ice thickness and the depth of water. SIPRE Report 36[8] and J. T. Wilson[11] have reported on the magnitude of the waves, and have related critical velocity to water depth and ice thickness. Situations have been reported in which a following vehicle in a formation has broken through the ice while the vehicle ahead and behind passed the point safely. One also hears from bush pilots and tractor train operators of examples of vehicles and planes moving toward shore breaking through as the water depth decreased, possibly cases of critical velocity.

Location Survey

With basic theory in mind, and with the new knowledge of safety beyond the initial cracking, as well as the limiting factors before us, we can focus on procedures developed for actual field operations.

This discussion will be restricted to the ice survey and will omit

Photo No. 7—C-124 Globemaster aircraft on ice runway with level for settlement observations.

Photo No. 8—Cleared ice strip with 3-in. snow wearing surface.

operational considerations such as size, obstructions, wind, visibility, and marking. However, it must be emphasized that the location party will include an operations man, preferably a pilot. In addition, it is recommended that the party have these members: an engineer, an ice scientist, and an Arctic specialist familiar with the area, climate, and native language. Transportation by air in small- or medium-weight, ski-equipped planes is best and allows the team to land almost at will.

An approach from the air to a prospective site allows complete observation of the area, and leads, pressure ridges, and the direction of snow drifting can be sketched. For sites on ocean ice, or large lakes, locations in bays or behind points of land are best for protection against the development of current cracks or leads. Also some protection from the wind is gained. Lakes and rivers are apt to develop cracks across narrow portions, and rafted ice or hummocking in shallow areas, so these locations should be avoided.

In selecting the direction and position of the strip, it is advantageous to use the controlling action radius, L. The body of water should preferably have a minimum width of 20 L, and the landing strip should be at least 10 L from shore. The best orientation of strip to shore is 45^0 to 60^0; a runway close and parallel to shore should be avoided.

After the landing, a careful reconnaissance is made of the selected area. If any of the local population is available much valuable information about currents, tides, action and location of cracks, seal holes, and climatic conditions can be obtained. Any active, or wet, crack is a potential danger, while old healed cracks and small thermal cracks need not be avoided. Since cracks will project to the surface of a snow cover, they can be located and investigated without extensive clearing. Cracks across the projected strip are much less of a danger than are cracks parallel to the strip.

Capability Determination

Thicknesses are measured as described previously. The number of these measurements will depend upon the ice thickness found and its regularity. Major variations in thickness indicate currents or springs which must be investigated carefully to locate all thin spots. Minimum coverage requires holes at touchdown, prop reversal, warm-up, parking, and unloading points. These thicknesses are compared to those recommended(8) for the type of aircraft anticipated.

The depth of water can be measured through these holes and compared to requirements based on critical velocity and resonance waves. A particularly bad situation to be avoided is that of ice extending from a free-floating condition to a ground-fast position. In this case a rough surface which would make operations hazardous is usually found, and with sea ice a working tidal crack will be found at the shore line. Land-fast ice and ice growing over very shallow water are best avoided, for the principles of the floating ice sheet may not apply. The ice is apt to break like a cracker if partially supported on rigid foundations instead of by a deflecting fluid foundation.

One larger hole is required to enable the observer to investigate the structure and layering. Modification of the thickness can then be made to account for weak layers such as slush or snow ice. Cored, or unaltered, samples are recommended where salinity determination is to be carried out.

In marginal cases it is advisable to establish more than one unloading and parking area, and perhaps more than one landing strip. Ice of marginal thickness may crack under load and should be used only for emergency operations. Ice cracks will heal in subfreezing temperatures and alternate use of two strips is possible. These runways should be at least 12 L apart to avoid superimposing deflection curves.

The existing snow cover should be measured and the possible presence of a water or slush layer above the ice investigated. This indicates cracking and sagging of the ice sheet under differential snow loads and perhaps preloading. There is a great danger of freezedown if the aircraft remains in place long. A touch-down approach will often indicate water and slush before the initial landing, and precautions can be taken.

Strength tests are normally not required for a given landing unless the ice thickness is minimum and the situation an emergency. However, assuming an engineer, and/or an ice scientist, is present, as recommended, strength tests will be most worthwhile for the data obtained will indicate to the trained personnel the limits of operation in the particular situation. In such a case, it is essential to have a qualified person make the tests and interpret the results. It is hoped that complete data will be available soon so that normal ice thickness requirements can be modified where necessary on the basis of "on the spot" temperature, salinity, and structure determination.

Operational Procedure and Control

Before final approval is given in marginal cases for which the ice thickness is barely sufficient based on average properties, it is recommended that a trial landing be made. It will be remembered that initial cracking does not constitute immediate failure, and that complete failure requires some elapsed time after the first crack. By careful observation of settlement of the surface with a level during landing and parking, the pilot can be informed of danger of breakthrough in time to move, or to take off. If deflection of the surface continues at a decreasing rate, the plane is safe. If the deflection increases at an increasing rate, the plane should take off. Initial cracking may be heard on fresh-water ice but is usually not seen since it occurs at the bottom of the sheet. If secondary cracking occurs as circumferential top cracks, complete failure of the ice sheet and breakthrough is unavoidable if the plane cannot be removed at once. Even so, in such a marginal case, only the landing gear will break through, and the plane will be supported on its wings. The need for carrying out such a test landing is dependent upon the demand for use under such marginal cases.

During the period of operations it is advisable to have a control procedure established and carried out. Since the major factors determining the ice sheet's capabilities are thickness and temperature, these become the control factors particularly during the spring period of deterioration. It is suggested that:

a) Average daily temperatures be recorded, and required thicknesses be determined for the given loads.

b) When temperatures exceed $10^{\circ}F$ for sea ice, and $24^{\circ}F$ for fresh-water ice, ice thickness should be checked every other day, and for temperatures near the freezing point, checked every day.

c) Long duration loads be watched for progressive sagging and moved when it develops.

d) In marginal cases of high temperatures and/or minimum thickness, aircraft should be observed with a level as previously described.

If a level is not available, the deflection of the ice can be observed by cutting a hole in the ice and watching the water level relative to the ice surface. Since this forms an escape valve for the water, the appreciable sagging might pond the area which is a severe disadvantage to operations until this water freezes.

During the period of the spring melt, surface deterioration will usually control. Surface softening and ponding of melt water make operations hazardous in many cases before the combination of thickness, temperature, and strength dictate the close of operations. Nevertheless, one must be very cautious in using sea ice during such a warm period for the brine content quickly reduces the sound ice to a porous, skeleton structure. SIPRE Report 36[8] shows this reduction in strength in requiring the following thicknesses for a C-54 aircraft with less than one hour of parking:

Fresh-water ice at 31°F air temperature: 32 in.
Salt-water ice at 28°F air temperature: 49 in.

This surface ice deterioration is retarded somewhat by leaving three or four inches of snow on the ice surface. Such a snow cover also functions as a much better wearing and frictional surface than clear ice and should be required at all times. Dark objects must be removed for they will create melt pockets in the ice surface.

Advantages

The obvious advantage of using lake, river, or ocean ice, for an airfield is that it is flat, and it is already there. Clearing and marking is all that is necessary to make the strip operational.

Also, a frozen body of water near an existing land field forms an emergency field even without clearing the snow.

Finally, a landing accident on an ice strip is less damaging to the plane and to personnel because the surface is less rigid and has less friction than a pavement surface.

Disadvantages

The airfield is only temporary unless one considers shelf ice or an ice island.

Visibility during landing may be poor especially in a whiteout.

Control during the landing roll may be poor if the ice is clear and crosswinds are blowing.

Finally, there is the remote possibility of breakthrough.

Recommendations

The information now available is the result of research programs at the Snow, Ice, and Permafrost Research Establishment, and formerly at the

Arctic Construction and Frost Effects Laboratory, both directed by the Corps of Engineers, U.S. Army.

Also it is a result of experience obtained in actual operation along the Dewline during the initial airlift, 1955. The recommendations made in this paper are based on this information.

To increase the fund of knowledge in this subject, it is recommended that as many as possible landings on ice, safe or otherwise, be recorded in detail and reported to SIPRE. Such data will be most valuable in developing a complete operating procedure.

ACKNOWLEDGMENTS

The author is indebted to the Snow, Ice, and Permafrost Research Establishment for making possible his participation in the research and operations upon which this paper is based, and particularly to Dr. Henri Bader, Chief Scientist, and to Mr. James Gillis, Administrator, for their support and counsel. The author is greatly indebted to Dr. Andrew Assur who, through many long discussions, contributed generously to our knowledge of ice sheets. The author is also grateful to Squadron Leader Scott Alexander, RCAF, for an education in life and survival in the Arctic.

REFERENCES

1. H. Hertz, "Uber das Gleichgewicht schwimmender elastischer Platten," Wiedemann's Annalen der Physik und Chemie, vol. 22, 1884.
2. H. M. Westergaard, "Stresses in Concrete Pavements Computed by Theoretical Analysis," Public Roads, vol. 7, no. 2, April 1926.
3. H. M. Westergaard, "Stresses in Concrete Runways of Airports," Proceedings, 19th Annual Meeting of the Highway Research Board, Dec., 1939.
4. A. Nadai, "Die elastischen Platten" (Julius Springer, Berlin), 1925.
5. F. Schleicher, "Uber Kreisplatten auf elastischer Unterlage," (Julius Springer, Berlin), 1926.
6. A. Assur, Engineer, SIPRE,* Unpublished work and personal communications.
7. SIPRE* Report No. 4. Review of the Properties of Snow and Ice. Jul., 1951.
8. SIPRE* Report No. 36. Airfields on Floating Ice Sheets. Jan., 1956.
9. SIPRE* Special Report No. 16. Airfields on Sea Ice, Oct., 1955.
10. S. Alexander, RCAF, "Location of an Ice Landing Strip," Edmonton, 4 July 1955. Personal Communication.
11. J. T. Wilson, "Coupling between Moving Loads and Flexural Waves in Floating Ice Sheets," SIPRE Report No. 34, 1955.

*Snow, Ice, and Permafrost Research Establishment, Corps of Engineers, U.S. Army.

Journal of the
AIR TRANSPORT DIVISION
Proceedings of the American Society of Civil Engineers

AIRFIELDS ON PERMAFROST*

Kenneth A. Linell,[1] A.M. ASCE
(Proc. Paper 1326)

FOREWORD

Symposium on Cold Regions Problems Air-Transport

Polar air routes and air bases north of the Arctic Circle have added a new and exciting dimension to the already scintillating field of air transport. Developments on this frontier have been made possible through the cooperative efforts of operating personnel and engineering technologists. In the Symposium, presented at the October 1956 Convention of the Society (of which this paper is a part), the part played by workers in an exacting field is dramatically written in statements of problem areas, in the results of their research, and in their hopes and anticipation of future application of their findings.

The five papers (Proc. Papers 1323 through 1327) and attendant discussions represent the most advanced knowledge available on cold regions air transport. The papers have been selected to take advantage of the special abilities of the authors, each of whom is an emminent authority, and to indicate for readers the opportunities and problems in this area of military and commercial transport significance.

ABSTRACT

In this paper the author outlines the special problems of constructing airfield pavements on permafrost foundations. Particular attention is devoted to problems of construction in areas of discontinuous permafrost, the importance of non-frost-susceptibility soils is shown, and means of combating degradation of pavements are carefully explained. The effects of frost loosening on subgrade soil compaction are outlined.

Note: Discussion open until December 1, 1957. Paper 1326 is part of the copyrighted Journal of the Air Transport Division of the American Society of Civil Engineers, Vol. 83, No. AT 1, July, 1957.

*Paper prepared for presentation at the Convention of the Society at Pittsburgh, Pa., October 16, 1956.

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INTRODUCTION

The special problems of constructing airfields on permafrost did not become apparent until World War II. When such construction was started in Alaska, Greenland, and Canada at that time, cost was definitely a secondary consideration, yet difficulties developed at some locations. At other locations, at which the sites selected had favorable natural subsurface conditions, fewer difficulties were encountered. These experiences brought out the realization that little was known about construction on permafrost and provided the spur to programs of research on this subject. The Corps of Engineers has now conducted such research for about a decade. In this time a great deal has been learned about frozen ground and about construction on permafrost; however, much more investigation and research is needed. Although the number of airfields constructed on permafrost has not increased materially, the problems inherent in such construction have multiplied. The great increases in weight and speed of aircraft over the past ten years have brought about requirements for longer and smoother runways of higher load-carrying capacity. The end of these developments does not yet appear in sight.

Basic Problems

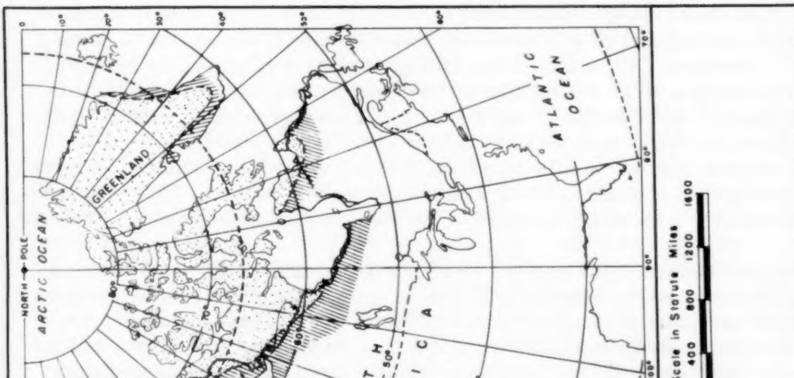
Problems common to any earthwork or paving operations in permafrost areas are: remoteness and limited accessibility, limited working seasons, difficulty of excavating and handling frozen ground, difficult drainage conditions, and hazard of degradation. These problems are discussed in detail in the following paragraphs.

a. Remoteness and Limited Accessibility. In general, the permafrost areas are remote from principal centers of civilization, as shown on Fig. 1, which is based on material from references (1) through (4). Generally, everything required for construction; equipment, personnel, and materials; except earth, gravel, stone, and water, must be imported, usually at very high costs because of the substantial distances and the lack of established transportation methods or routes.

b. Limited Working Seasons. In the permafrost regions the period during the summer when air temperatures are above freezing is generally less than 6 months and may be as little as 3 months. Thus, it is necessary to work around the clock during these few months in order to accomplish as much work as possible. While some types of construction can be carried on through the winter months, earth-moving and paving operations are generally halted by low temperatures and blowing snow.

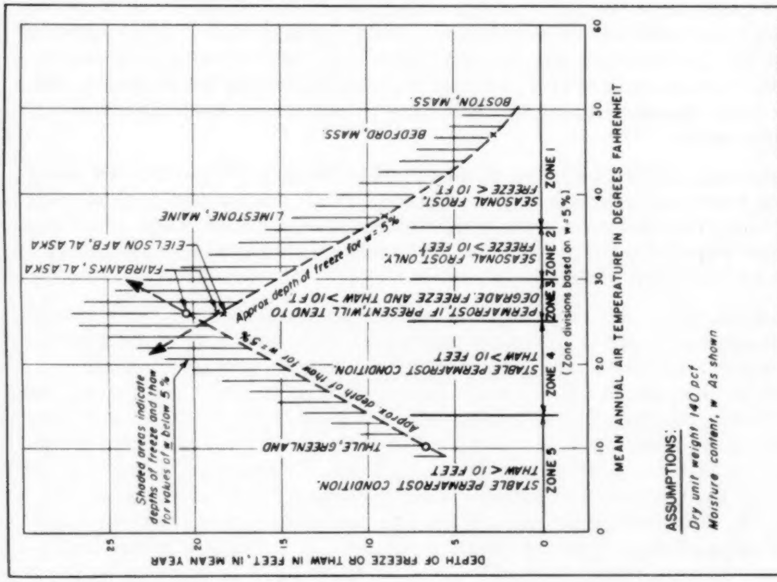
c. Difficulty of Excavating and Handling Frozen Ground. At the start of the summer work season, April to June, the ground is solidly frozen from the surface down, usually to a substantial depth. (At Thule, Greenland, the bottom of permafrost is estimated to be at a depth of 1600 ft). At this time the temperature of the ground between depths of 5 to 15 ft is near its lowest level for the entire year or is only partially recovered therefrom.

Tests show that saturated frozen soils have very substantial strengths which increase markedly with lowering of temperature below $32^{o}F$ at $25^{o}F$, for example, compressive strengths may vary from 300 psi to 1000 psi or more.[5] At still lower temperatures, strength properties may approximate



APPROXIMATE DISTRIBUTION OF PERMAFROST IN NORTH AMERICA

FIGURE 1



FREEZE AND THAW PENETRATION FOR BITUMINOUS-PAVED AREAS OVER WELL-DRAINED GRAVEL

FIGURE 2

those of moderately-strong Portland cement concrete. Excavation therefore is difficult and earth-moving operations present a major problem to construction forces. As thaw progresses from the surface downward, fine-grained soils may turn to mud. Free-draining granular materials thaw rapidly, but even in these deposits it may be necessary to excavate with shallow cuts over large areas.

d. Drainage Conditions. The presence of an impervious permafrost layer prevents downward drainage in the summer. Thus, permafrost regions tend to be swamp-like and poorly drained. Any excavation tends to act as a sump, into which water will drain from the surrounding thawing soil, thus making earth cuts a difficult problem.

e. Degradation. The change of the surface temperature conditions caused by the construction of the pavement may cause some lowering of the permafrost level. In the more southerly permafrost regions this may initiate progressive degradation in which the level continues to lower year after year. If the frozen ground contains lenses, veins, or masses of ice, as is common, lowering of the permafrost level will cause such ice to thaw and drain away, resulting in settlement of the overlying surfaces. Degradation effects are increased by the tendency for ground-water movement to produce differential thawing, the flow tending to concentrate into subsurface thaw channels which are self-intensifying. Under extreme conditions, in a single summer degradation can cause a gravel road to become so rough as to be impossable for a jeep.

However, degradation under completed construction more frequently progresses at a much slower rate. Under 26 pavement-test sections at the Corps of Engineers' Fairbanks, Alaska, Permafrost Research Area, in observations covering the period 1948-1956, lowering of the permafrost table has varied from a negligible amount to a maximum average rate of about 7 in. per year, discounting thaw which occurred during the initial construction.(4) However, only a few inches of degradation may seriously disturb pavement grades if the ice content of the thawing strata is high.

Terzaghi(6) and Carlson(7) have shown that permafrost can thaw upward from below at only a very slow rate; Terzaghi has estimated a rate of less than 2 cm per year for a soil containing 30% ice by volume, and Carlson has estimated a rate of about 2/3 this amount for Umiat, Alaska. Thus, degradation is one of the principal hazards in the construction of airfields on permafrost.

The combination of the unfavorable factors of remoteness, poor accessibility, limited working season, difficulty of excavating ground in the frozen condition, and poor drainage makes construction in permafrost areas extremely costly. In the past, this condition has been compounded by a lack of adequate engineering design data applicable to construction on permafrost. Subsurface exploration, necessary for adequate planning, has frequently been superficial, or has been skipped entirely due to the great difficulty and expense of such work, or due to the substantial delays in the project which would ensue while such information was being obtained. The latter factors have frequently made it necessary for design engineers to make extremely conservative assumptions. These have further increased costs.

Because of the high costs attendant upon construction in most permafrost areas, it becomes even more important than in temperate-zone construction

that designs be refined to eliminate all unnecessary expenditures, provisions, or factors of safety. Money spent on research which will permit such refinements offers the opportunity for repayment many times by future savings. The savings on a single large construction project may pay for an entire program of research.

Effect of Modern Aircraft upon the Problem

The development of jet aircraft has intensified the problems of constructing airfields on permafrost. Experience with these aircraft indicates that, because of the type of undercarriage, the flexibility of their wings, and their high landing and take-off speeds, pavement roughness hitherto considered minor and visually undiscernable to a person standing on the pavement, may seriously interfere with the taxiing, take-off, and landing operations. This may threaten loss of control of the aircraft through "porpoising" and cause undue stresses in the aircraft, undercarriage, and tires. As a result, the Corps of Engineers now requires that runway pavements be constructed so the final surfaces are within 0.04 ft of the design elevation, and that when tested for trueness with a 12-ft straight-edge variations shall not exceed 1/8 in. in the direction parallel to center line and 3/16 to 1/4 in. transversely, depending on the transverse grade. Design and construction of pavements which will initially and permanently conform to these requirements presents a substantial challenge in non-frost and seasonal frost areas. In permafrost areas it becomes a serious problem if the construction involves soils which are susceptible to frost action. In the Arctic and Sub-Arctic the surface elevations of such soils are relatively stationary only during the winter months, after the active zone has become completely frozen. During the thawing period, from late spring until fall, the surface continually subsides as the ice in the subgrade thaws. Grade stakes set during the thawing and freeze-back periods are soon significantly in error. Pavement laid to a given elevation one week is out of grade with respect to pavement laid to the same elevation a few weeks later. At the Fairbanks Research Area of the Corps of Engineers pavements, 3 to 4 ft thick built on a silt subgrade, show average differences in elevation of 2-1/2 to 3 in. between the end of summer and late winter, under conditions of minor ice segregation. These pavements exhibit rates of settlement of the order of 1/4 in. per week during June and July. Under conditions of substantial ice segregation and heave values of elevation differences and rates of settlement are substantially higher and grade-setting problems are correspondingly greater. Temporary bench marks set in the active zone are subject to similar errors. The situation is further complicated because the depth of subgrade thaw at a given point on a given date during the summer of construction is unlikely to be the same as that which will occur on the same date in subsequent years. This difference will be variable and dependent on the timing of the various pavement-construction operations.

Control of Surface Roughness

In general, it does not matter if the whole pavement rises and falls a few inches through the year, provided the rise and fall is uniform, over the entire pavement and the surface remains smooth and sound. Excessive cracking

may result in a spalling condition which is a source of damage and hazard to jet aircraft. It is also necessary that adequate bearing capacity be maintained, and that no drainage problems, as at hangars, are created by the heave. To produce a pavement which has these characteristics initially and will retain them under freeze and thaw conditions, when the subgrade conditions are adverse, requires detailed study of the subgrade soil conditions, of the rate and sequence of construction operations, and of elements, such as culverts, which break the continuity of the subgrade conditions.

In continental United States it is feasible to use sufficient thickness of pavement and non-frost-susceptible base to provide substantially full protection so freezing will significantly penetrate the subgrade during most years. Farther north, however, the depth of base required for full protection becomes excessively large, as much as 15 to 20 ft or even more. In Arctic areas the climate becomes so cold that full protection is feasible again, in these locations restricting thaw to the base-course soils. This situation is illustrated in Fig. 2 which is based on field observations, adjusted by computations so as to be on a common basis and to represent mean conditions. The dashed lines on Fig. 2 show approximate depths of freeze and thaw for a gravel containing 5% moisture, under a bituminous pavement kept clear of snow in winter. The shaded area indicates that depths of freeze and thaw for moisture contents below 5% will be greater.[2] For given climatic surface conditions, depths of freeze and thaw are determined largely by the soil moisture content. Therefore, the depths of freeze and thaw would be increased for lower base-course-moisture contents and decreased if the reverse were true. It is evident that, within reasonable limits, it is desirable that the material underlying the pavement have a moderate moisture-holding capacity in order to limit the depths of freeze and thaw, but not have so many fines as to be frost susceptible.

It will be noted that the curves of depth of freeze and thaw for 5% moisture intersect approximately at a mean annual temperature of 25°F. At higher temperatures the depth of thaw exceeds the depth of freeze and degradation will tend to occur under bituminous pavements if permafrost is present. At mean annual temperatures below 25°F degradation will not occur if sufficient soil cover is provided over any ice masses which are present in the foundation. In this latter case the depth thawed during the summer will freeze back completely during the winter. If the soil cover over ice masses is not sufficient at temperatures below 25°F some of the underlying ice will thaw during the summer. This will result in settlement which will be progressive year after year even though freeze back is complete each winter. However, stability will ultimately occur if the ice contains sufficient soil to gradually build up a protective cover. This will be aided by any material added at the surface in pavement-leveling operations made necessary by the settlement.

The data on Fig. 2 are intended for illustration only and the reader is cautioned against attempting to use data from the figure for quantitative design at specific locations. The plot is based on a limited number of measurements and more would be desirable. At moisture contents other than 5%, different critical mean-annual temperatures than 25°F should be expected because of changes in the ratio between thermal conductivities in the frozen and thawed states. Also, two locations with the same mean-annual air temperature

2. Individual measurements in gravel under the pavements at Thule AFB, Greenland, have run as low as 1%.

may have substantially different amplitudes between summer and winter temperatures and hence different depths of freeze and thaw. Again, the mean-annual air temperature, which forms the abscissa scale of the graph, does not reflect the variable effects from place to place of such factors as solar radiation and wind velocity on the depths of freeze and thaw. However, the figure does illustrate certain basic relationships which must be considered in the design and construction of airfield pavements on permafrost.

Since correlation of depth of freeze and thaw is made with the mean annual temperatures, field results will deviate from mean performance in individual years. If it is desired to provide full-protection design for seasons more severe than the mean, such as the winter which will occur with a frequency of once in 10 years, it will be necessary to use greater depth of non-frost susceptible material than indicated by Fig. 2, on which the plotted penetrations correspond to mean values. At locations where the mean depths of freeze and thaw under pavements are nearly equal, a summer with an above-average thawing index may result in a temporary residual thaw zone which may give the impression of a degrading condition until a winter occurs which is sufficiently cold to reproduce complete refreeze.

It may be arbitrarily assumed for this analysis that 10 ft of non-frost-susceptible fill is the maximum that may be economically placed in constructing an airfield for heavy planes. Fig. 2 indicates that, for material of 5% moisture content, 10 ft of depth corresponds to a mean-annual air temperature of 14°F on the thaw curve and 36°F on the freeze curve.

Available data indicate that permafrost does not normally exist under any conditions of natural surface cover or climate where the mean-annual air temperature exceeds 30°F, although theoretical studies indicate such may be possible. In the range of temperatures between 30°F and the temperature for which the depths of freeze and thaw under pavements are equal permafrost may or may not be present under natural conditions, depending on local factors. In this range, however, permafrost may, as previously stated, be expected always to tend to degrade when a bituminous pavement has been placed and kept clear of snow. In this range of mean annual temperatures the depth and extent of permafrost is greater with lower temperatures. The temperature at which permafrost becomes essentially continuous under natural conditions of surface cover does not necessarily correspond, however, with the temperature at which the estimated depths of freeze and thaw under pavements are equal. Heavy snow cover may, for example, substantially modify the effects of winter freezing conditions and restrict the development of permafrost. In some places, it is possible that permafrost does not exist under natural conditions but will tend to develop subsequent to construction under areas kept clear of snow. Below 25°F, the permafrost areas may be divided into two zones for which the required thickness of non-frost-susceptible soil for full protection are over 10 ft and under 10 ft, respectively. Thus, five zones may be visualized for the entire frost region of the Northern Hemisphere. In these zones various degrees of difficulty may be expected in the design and construction of satisfactory pavements. The five zones are indicated on Fig. 2 and shown on a map of North America and Greenland in Fig. 3. In general, the engineering problems of providing satisfactory airfields are considered most difficult for Zone 3, with Zones 4, 2, 5, and 1 following in order of decreasing difficulty. However, construction costs are not necessarily in proportion to the design difficulties.

In Zone 3 there is, in general, no practical method by which permafrost

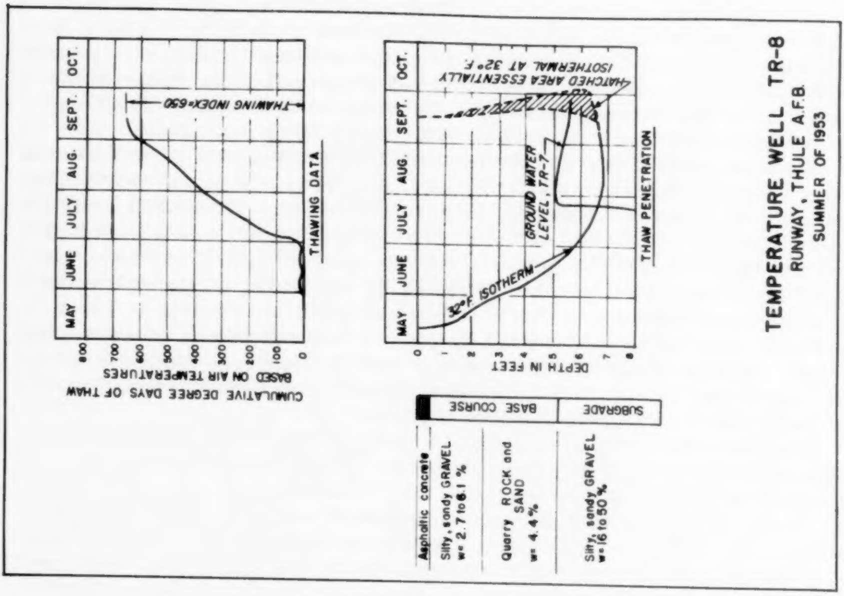


FIGURE 4

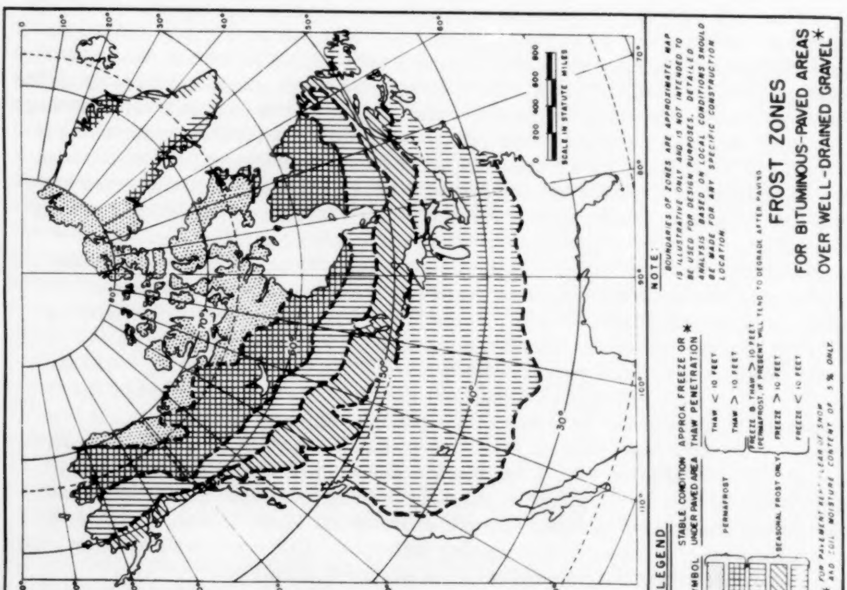


FIGURE 3

can be prevented from tending to degrade when a pavement is constructed over it. Near the northern limit of this zone the use of a white or reflective surface might prove effective but would offer operating and maintenance disadvantages. The use of artificial refrigeration to keep the ground frozen, or the use of a pile-supported structural deck with air space between deck and ground would be prohibitively expensive, except possibly as limited military expedients. While use of a special insulating material under the pavement would slow the rate of degradation, it would not halt it. The remaining engineering solutions are as follows:

a. The only satisfactory solution is to select a site which does not contain bodies of ground ice or select an alinement on ground from which permafrost is absent.

b. The foundation might be pre-thawed by steam or water points. This would be a major task, particularly if the permafrost layer is to 100 to 200 ft thick. In the latter case pre-thawing to partial depth would have to be considered, the potential gains being a very slow rate of degradation and a tendency for differential thaw settlements to be smoothed by the resulting relatively thick cover of thawed soil. However, the latter scheme is filled with uncertainties at the present state of knowledge.

c. The pavement might be constructed with a substantial base of non-frost-susceptible materials to minimize the annual heave and settlement and to reduce the rate of degradation in the early years. Reliance would be placed on heavy and continuous maintenance to insure an adequate surface. However, for many subgrade conditions this method could not continuously provide an airfield sufficiently smooth for modern aircraft.

Fig. 4 illustrates 1953 summer-thaw conditions under the bituminous concrete runway at Thule AFB, Greenland. Conditions at this site are typical of extreme Northern conditions, i.e., Zone 5 on Figs. 2 and 3. It will be noted that thaw penetration started about the end of the first week in May and progressed rapidly, even though substantial accumulation of degree days of thaw did not begin until about the start of the last week in June. By this time thaw had reached a depth of over 5 ft. The heat required for this thaw penetration could only have come from solar radiation heating of the pavement surface. At this time of the year the sun is above the horizon 24 hours of the day in this high Northern latitude. Its heating effect is continuous as long as the sky is not clouded.

Fig. 4 also shows that the rate of thaw penetration slowed markedly after the first of July, even though warm air temperatures resulted in a rapid accumulation of degree days of thaw. This slowing is attributed to a combination of factors which include the increasing moisture content of the soil with depth, the insulating effect of the over-lying thawed layers, and the reduced heating effect of the sun past the summer solstice. Fig. 4 shows that there was a slight rise in the freezing level after mid-August, due to freezing from below, although average-daily air temperatures continued to result in accumulation of degree days of thaw. After 12 September air temperatures dropped rapidly and the entire thawed-depth froze completely in 2 or 3 weeks. The dashed curves and cross-hatching at the end of the thaw penetration curve indicates a brief period during which the soil was at substantially the same temperature throughout the depths indicated by the hatching.

It is apparent from Fig. 4 that an airfield will be stable if constructed so

the materials within the depth of annual thaw and freeze are not susceptible to frost damage. This is the reason that airfield design for northern Arctic areas is considered in some ways less difficult than designs for more southerly Arctic and Sub-Arctic regions.

The preceding discussion has approached the problem from the point of view of providing sufficient thickness of non-frost-susceptible materials so the underlying frost-susceptible soils are not affected by annual freeze and thaw. An alternate design approach, which has been used by the Corps of Engineers for about ten years, is to provide only sufficient thickness of non-frost-susceptible material so sufficient load-carrying capacity will be available at all times during the thaw period. Design charts for this assumption, based on an extensive series of traffic tests performed during Spring thaw periods, are given in Corps of Engineers' design manuals.(8) Since relatively deep freeze-and-thaw penetration may occur in frost-susceptible soils under the base course, frost heave may be considerable under this design method. A pavement which will be sufficiently smooth for future aircraft requirements cannot be assured by direct and unmodified application of these reduced-strength design criteria. Research may show it possible, in areas of deep freeze and thaw, to employ thicknesses which are intermediate between those yielded by the latter criteria and those required for full protection. Advantages may be gained by utilizing one or more of the potential modifying steps which follow: by allowing some freeze-thaw penetration of subgrade, by insuring uniformity of frost action, by taking into account the heave-reducing effect of load, by using admixtures to alter frost susceptibility, or by painting pavement white.

a. Allowing some Freeze-Thaw Penetration of Subgrade. Both theory and field observations show that freeze and thaw penetration are sharply slowed upon reaching relatively-moist subgrade soil under a free-draining base course of relatively low moisture content. The lower-thermal-conductivity base course controls and limits the flow of heat into or out of the subgrade material of relatively high volumetric heat content. Under conditions which would not produce roughening or loss of compaction beyond permissable limits, some penetration of freeze and thaw into the subgrade might be permitted. This would result in a reduction in the required thickness of base course. Such a reduction would be possible only if the layer of non-frost-susceptible material exceeds the thickness required for load-support during the frost-melting period and if subgrade conditions are uniform.

b. Insuring Adequately-Uniform Frost Action in Subgrade. Under favorable conditions, the effects of differential heave and settlement which result from annual freeze and thaw may be markedly reduced by allowing only gradual transitions of foundation-soil and moisture conditions. A hazard beyond control is that frost action may develop at a number of individual locations, rather than uniformly, so the resulting frost heave is non-uniform. This is less likely in clay than in more pervious soils, such as silty sand. In clay soils moisture cannot move substantial distances to contribute to the development of ice lenses.

c. Taking Advantage of the Heave-Reducing Effect of Load. Laboratory and field tests have indicated a reduction in frost heave under thicker base courses.(9) This seems due to the direct effect of the weight of the pavement and base in modifying the amount of ice segregation, as well as to some

reduction in the depth of subgrade which is frozen. It is possible that this effect may permit some additional reduction in base thickness in cases where some freeze-thaw penetration of the subgrade, with controlled frost heave, is to be allowed. Field tests to evaluate this effect in greater detail are now being planned by the Arctic Construction and Frost Effects Laboratory.

d. Use of Admixtures. The Arctic Construction and Frost Effects Laboratory has sponsored studies for some years aimed at developing admixtures which may be used to modify the frost activity of soils. Some have been discovered which are very effective in laboratory tests,[10] but field testing has not yet been carried out. Economical methods of introducing the materials into the soils need to be developed, and their degree of permanency needs to be demonstrated. However, there are attractive possibilities that admixtures might in the future be used with frost-susceptible soils readily available on the site to build up a base structure of satisfactorily-low frost susceptibility. It appears that the greatest potential for such applications is granular fill material of border-line frost susceptibility.

e. Painting Pavement White. Recent experiments by the Army Corps of Engineers at Thule AFB have shown that painting bituminous-concrete pavement with white paint substantially reduces the depth of thaw penetration. As shown in Fig. 5, depth of thaw penetration under a taxiway was 1.9 ft less under the white pavement than under the black one, and freeze back occurred more quickly. The surface temperature during the summer averaged about 5°C lower for the white pavement than for the black. Unfortunately, white pavements are considered undesirable from the operating point of view because snow and ice melt less rapidly on these pavements.

Site Selection

All the above schemes, even if employed successfully, are poor substitutes for good site selection. Enormous savings result when it is possible to locate an airfield on granular, non-frost-susceptible soils rather than on troublesome fine-grained soils. For new major bases the importance and value of large-scale preliminary studies of foundation conditions cannot be overemphasized. Aerial photography is of special importance in site selection in permafrost areas.[11][12] Frequently, soil polygons and other surface features are apparent on aerial photographs while difficult to discern on the ground. In Arctic areas, relatively deep deposits of clean, well-drained, pervious sands and gravels offer ideal construction conditions. For these locations the designs can be similar in many ways to those used in non-permafrost areas. Sites should be selected which will permit pavement embankments to be constructed of granular, free-draining, non-frost-susceptible materials. Runway alignments requiring cuts should be avoided. When cuts encounter ice masses the resultant thawing and settling of the pavement may be serious and may continue for years. Cuts are a source of drainage problems. Drainage during the summer thawing period tends to flow into depressions below the surrounding terrain, and underdrains are of doubtful value because of their tendency to become blocked by ice. Excavation of cuts is frequently difficult to handle. North slopes give more trouble than south slopes. Because of the flat angle at which the sun strikes north slopes, these receive less solar radiation and the permafrost tends to be nearer the surface.

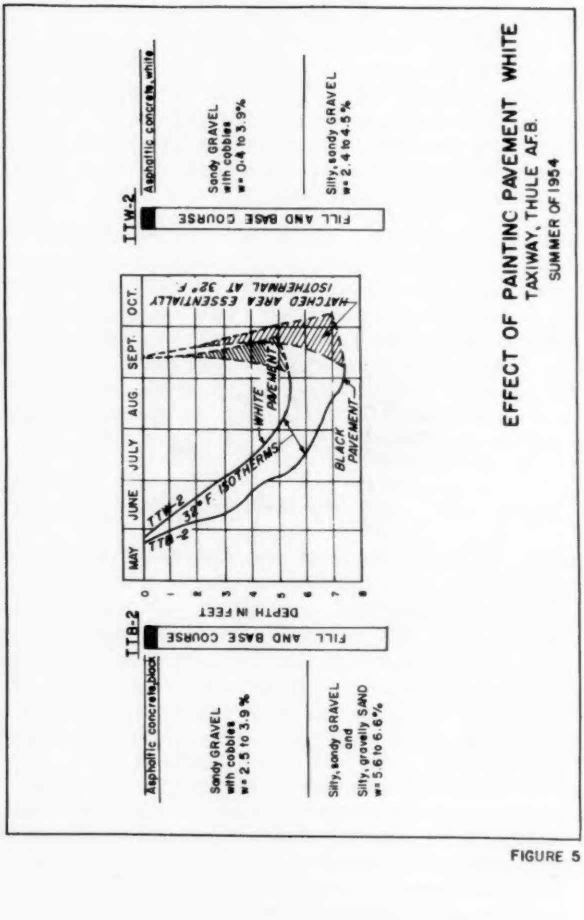

EFFECT OF PAINTING PAVEMENT WHITE
TAXIWAY, THULE A.F.B.
SUMMER OF 1954
TTB-2
Asphaltic concrete, black
FILL AND BASE COURSE
Sandy GRAVEL with cobbles w= 2.5 to 3.9%
Silty, sandy GRAVEL and Silty, gravelly SAND w= 5.6 to 6.6%
DEPTH IN FEET
0 1 2 3 4 5 6 7 8
MAY JUNE JULY AUG. SEPT. OCT.
TTW-2
TTB-2
32° F. ISOTHERMS
WHITE PAVEMENT
BLACK PAVEMENT
HATCHED AREA ESSENTIALLY ISOTHERMAL AT 32° F.
TTW-2
Asphaltic concrete, white
FILL AND BASE COURSE
Sandy GRAVEL with cobbles w= 0.4 to 3.9%
Silty, sandy GRAVEL w= 2.4 to 4.5%

FIGURE 5

Permanence of Compaction

The Corps of Engineers' compaction requirements for construction of flexible airfield pavements for very heavy aircraft are tabulated below.

Required Depths of Compaction Under Flexible Pavements for 240,000-lb Load on Twin-Twin Assembly

Percent Modified-AASHO Compaction	Depth of Compaction, ft Cohesionless Materials	Cohesive Materials
100	4-1/2	2-1/2
95	8	4-1/2
90	11	6
85	15	8
80	-	10

For rigid pavements, all base course materials must be compacted to 95% or 100%, depending on depth. Requirements for subgrades vary from 90 to 100%, to depths not exceeding 2 ft below the top of the subgrade. For rigid pavements, requirements are the same for all weights of aircraft.

It will be apparent from the previous abstract that compaction requirements are very stringent for modern aircraft loadings, and are considerably more critical for flexible than for rigid pavements.

Obviously, such requirements would be meaningless if the compaction was lost in a few years through frost action. The effect would be roughening of the pavement surface, differential compaction under traffic, and reduction in bearing capacity. Few quantitative data are available concerning frost loosening. In a clayey-till test fill placed at 100% Modified-AASHO compaction in 1950 and tested every year through 1953, measurements at the end of the first winter indicated a drop to about 95% compaction after thawing; thereafter there was little change.(13) While frozen, however, the average compaction was generally below 90% each winter, as a result of ice segregation. The data indicate that this particular material suffered a permanent loss of compaction which was somewhat less than might have been expected. Apparently the surcharge weight of 7 to 24 in. of overlying gravel base plus the weight of the material itself was sufficient to largely eliminate the void spaces formed by ice segregation after each thawing period. The area was not trafficked.

The data outlined above are preliminary and additional quantitative data for all types of soil are needed before the long-time effects of frost action on compaction can be evaluated.

A reduction in compaction from 100% to 95% would not be tolerable under pavements designed for heavy aircraft. Thus, it is necessary that soils subject to frost-action loosening be used only below the level at which the ultimate compaction will meet the requirements outlined. This is a criterion which is applicable to both permafrost and seasonal-frost areas.

CLOSURE

It is apparent that in construction of airfields in permafrost areas engineers must be prepared to solve not only all the problems encountered in non-frost areas but also an entirely separate and additional family of problems peculiar to these cold regions.

REFERENCES

1. Jenness, John L., "Permafrost in Canada," Arctic, Vol. 2, No. 1, pp. 13-27, May 1949.

2. Pihlainen, J., Data on occurrence and distribution of permafrost in Canada compiled by Permafrost Section, Division of Building Research, National Research Council of Canada, Ottawa (unpublished). Letter communication, Dec. 1956.

3. Hopkins, David M., Karlstrom, Thor N. V., and others. "Permafrost and Ground Water in Alaska." U.S. Geological Survey Professional Paper 264-F, Washington, D.C., 1955.

4. Corps of Engineers, U.S. Army, Arctic Construction and Frost Effects Laboratory, Unpublished ground temperature and permafrost records from Alaska and Greenland.

5. Corps of Engineers, U.S. Army, Arctic Construction and Frost Effects Laboratory. Investigation of Description, Classification and Strength Properties of Frozen Soils, Fiscal Year 1951. SIPRE Report 8, in two vols. Snow, Ice, and Permafrost Research Establishment, June 1952.

6. Terzaghi, K., "Permafrost," Journal, Boston Society of Civil Engineers, Vol. 39, No. 1, Jan. 1952.

7. Carlson, Harry, "Calculation of Depth of Thaw in Frozen Ground." In "Frost Action in Soils, A Symposium," Highway Research Board, Special Report No. 2, Washington, D.C., 1952.

8. Corps of Engineers, U.S. Army, Engineering Manual for Military Construction, Part XV, Arctic Construction. Chapters 1-7, Oct., Dec. 1954.

9. Corps of Engineers, U.S. Army, Arctic Construction and Frost Effects Laboratory, Cold Room Studies, Third Interim Report of Investigations with 4 appendices, in 2 vols. (In preparation), together with unpublished field data.

10. T. William Lambe, Modification of Frost-Heaving Soils with Additives Investigations 1953 through 1955. Prepared for Arctic Construction and Frost Effects Laboratory (in preparation for publication).

11. Frost, Robert E., "Interpretation of Permafrost Features from Airphotos." In "Frost Action in Soils, A Symposium," Highway Research Board, Special Report No. 2, Washington, D.C., 1952.

12. Purdue University, Engineering Experiment Station, Evaluation of Soils and Permafrost Conditions in the Territory of Alaska by Means of Aerial Photographs, in 2 vols. Prepared by Robert E. Frost for St. Paul

District, Corps of Engineers, for Airfields Branch, Engineering Division, Military Construction, Office of the Chief of Engineers, U.S. Army, Sept. 1950.

13. Corps of Engineers, U.S. Army, Arctic Construction and Frost Effects Laboratory, Final Report of Field Investigations at Frost Test Section, Loring AFB, Maine (in preparation).

Journal of the
AIR TRANSPORT DIVISION
Proceedings of the American Society of Civil Engineers

WHITE-OUT, A HAZARD TO ARCTIC FLYING

R. W. Gerdel,* M. ASCE, and M. Diamond**
(Proc. Paper 1327)

FOREWORD

Symposium on Cold Regions Air-Transport Problems

Polar air routes and air bases north of the Arctic Circle have added a new and exciting dimension to the already scintillating field of air transport. Developments on this frontier have been made possible through the cooperative efforts of operating personnel and engineering technologists. In the Symposium, presented at the October 1956 Convention of the Society (of which this paper is a part), the part played by workers in an exacting field is dramatically written in statements of problem areas, in the results of their research, and in their hopes and anticipation of future application of their findings.

The five papers (Proc. Papers 1323 through 1327) and attendant discussions represent the most advanced knowledge available on cold regions air transport. The papers have been selected to take advantage of the special abilities of the authors, each of whom is an emminent authority, and to indicate for readers the opportunities and problems in this area of military and commercial transport significance.

ABSTRACT

The studies on Arctic white-out reported in this paper were conducted at a field research station located on the Greenland Ice Cap, about 230 miles east of the Thule Air Base, and at an elevation of about 7,000 ft. The

Note: Discussion open until December 1, 1957. Paper 1327 is part of the copyrighted Journal of the Air Transport Division of the American Society of Civil Engineers, Vol. 83, No. AT 1, July, 1957.

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authors discuss five white-out phenomena, analyze the possibility of frecasting these phenomena, and suggest methods of dispersal.

INTRODUCTION

The term white-out has been used in the past by Arctic and Antarctic explorers and more recently by aircraft pilots to describe an atmospheric condition in which there is a lack of contrast between the sky and the snow surface. This condition in its most common form is the product of either a continuous cloud cover or a fog. Occasionally, this term has been applied to conditions where visibility has been reduced by precipitation or by windblown snow.

The rapid expansion in flying in the Arctic and Antarctic in recent years has been accompanied by an increase in the frequency of accidents attributable to white-out. The hazards created by this peculiar meteorological phenomenon are well recognized by most aircraft pilots on Arctic or Antarctic duty.

Most of the specific references to be found in the literature on white-out are little more than the subjective description of the experience of some flight officer or exploration party. As an example, Lieutenant Church (1946) in the Bulletin of the American Meteorological Society described his experience with white-out as "flying in a bowl of milk."

During a trip with a tractor-hauled freight swing in the summer of 1954 to a point more than 200 miles east of Thule, Greenland, both fog and stratus type white-outs were encountered frequently at elevations from less than 1000 ft to over 7000 ft on the ice cap. At times the tractor train was immobilized for several hours by a reduction in visibility to less than 200 yds. The photographs, Figs. 1 to 3, effectively illustrate the white-out conditions which may not only immobilize the train but also prevent support from the air.

The fog-type white-out, shown in Fig. 2, persisted for more than 14 hours during which the air temperature varied from 18°F to 27°F. The fog consisted of supercooled water droplets which were deposited as rime on some parts of the tractor train. In spite of a reduction in horizontal visibility to a few hundred yards, the fog layer was so thin that the blue sky frequently could be seen overhead.

During the period when the low stratus cloud cover produced the type of white-out shown in Fig. 3 there were frequent but brief intervals when the cloud cover lowered to contact with the snow surface producing a fog-type white-out.

Fog-type white-outs of supercooled water droplets often occurred at temperatures of 18°F to 20°F at one of the research sites on the Ice Cap during the summers of 1954, 1955, and 1956. The colloidal instability of this type of fog was demonstrated by the rapid shift from supercooled water droplets to ice crystals and back to the liquid-droplet phase as the fog was advectively transported past the station. Horizontal visibility varied rapidly from a few hundred yards to several thousand yards as the supercooled water droplets were replaced by or converted to ice crystals which at times, through collision or accretion, became large enough to fall out as precipitation. Probably the most unexpected phenomena associated with some of the supercooled water droplet and ice-fog white-outs was the presence of wind velocities of 10 knots or more.

It was not possible to determine whether the ice crystals were being formed locally or whether they were being transported to the site by the high winds. The crystals frequently were such extremely small, perfectly formed, individual needles, capped columns, and dendrites that it appeared probable they were formed locally.

The white-outs observed on the Greenland Ice Cap which produced some reduction in visibility could be divided in the following classes:

1. Overcast White-out. A product of complete cloud cover with light reflection between snow surface and cloud base. Perspective, involving the judgment of distance, was limited to a few feet but actual horizontal visibility of dark objects was not materially reduced.

2. Water-fog White-out. Produced by thin clouds containing supercooled, almost microscopic water droplets, with the cloud base usually in contact with the cold snow surface. This was the fog type of white-out which has been described as "milky" or "cottony." Visibility, both horizontally and vertically, was affected by the size and distribution of the water droplets suspended in the air.

3. Ice-fog White-out. Produced by clouds containing minute ice crystals, with the cloud base usually in contact with the snow surface. Frequently accompanied by brilliant spectral reflections from the small crystals and occasionally by bright bands or spots of refracted light. The mass of ice crystals suspended in the air determined the extent of visibility. This type of white-out frequently integraded with the water-fog form described above.

4. Blowing Snow White-out. Fine blowing snow plucked from the snow surface and suspended in the lower 3 to 4 ft of air by winds of 20 knots or more. The suspended fine grains of snow reflected and diffused sunlight and reduced visibility. Trail markers became difficult to see and features on the white snow surface difficult to identify during the periods of persistently high winds accompanied by blowing snow.

5. Precipitation White-out. Although all forms of falling snow reduced visibility, a storm characterized by very small wind-driven snow crystals falling from low clouds, above which the sun was shining, produced a white-out condition. The confusion caused by multiple reflection of light between the snow surface and cloud base was further complicated by the spectral reflection from the snow flakes and obscuration of land marks by the falling snow.

The fog and stratus types of white-out appear to present the greatest impediment to both air and ground transportation over the ice cap, particularly during the period from April to September. Some knowledge of the meteorological processes which are associated with their genesis might lead to development of methods for forecasting their occurrence with resulting improvement in the scheduling of aircraft movement or even to means for inducing artificial dispersion of the fogs.

Byers (1944) has stated that it is difficult to define a fog, for it is really a stratus cloud that forms at or close to the ground surface. A review of the fog-producing processes described by Willet (1928) and by Petterssen (1940) indicates that the fog, and possibly the low-stratus forms of white-out may be the product of any one, or a combination of several of the following processes:

a. Advection of warm sea air over the cold snow surface.
b. Radiation cooling of the snow surface and of the layer of air above the surface.
c. Upslope movement and adiabatic expansion of rapidly uplifted moist air.
d. Frontal passage with mixing of warm and cold air or with accompanying clouds forming a complete overcast.

Studies made by the 8th Weather Squadron (1953) indicate that the summer fog at Thule, Greenland is the advective type, produced by warm moist air flowing northward over Davis Strait and Baffin Bay. (Refer to map, Fig. 7.)

In a more recent study of fog, made by the 5th Weather Group, Detachment 24, (1956) it is stated that the most frequent and reliable cause of summer fog at the Thule Air Base is the presence of a low cell over Thule or within 200 miles east or noth, which is associated with or originated from a low in Davis Strait and accompanied by a trough over the West Greenland coast. The fog forms as the low cell moves north from near Uperhavik and reaches a point due east of Thule. This group found no relationship between wind direction up to 4000 ft and the formation of summer fog. From sounding data it was determined that 95% of summer fogs occurred when the 700-mb air temperature was above -16^{0}F. From an examination of the weather records for the summer of 1955 from two permanent stations on the Ice Cap designated as Site 1 and Site 2, which require year-around support by aircraft, it was concluded that the tendencies at these stations paralleled those at Thule; that there was no temperature characteristic peculiar to fog at these two stations; and that no useful correlation existed between fog and wind speed or wind direction at the Ice Cap sites.

The results of the studies made by SIPRE on white-out at its Ice Cap research station at Site 2, located at an elevation of 7000 ft about 230 miles east of Thule, along with the analysis of several years of meteorological records from both Site 1 and Site 2, indicate that there may be some potentially useable relationships between certain observable meteorological phenomena and the occurrence of white-out at the Ice Cap stations. Routine meteorological observations have been made at both sites since the Fall of 1953. At the present time, however, there are insufficient records from too sparse a network of stations to permit direct correlation of phenomena occurring on the Ice Cap with the synoptic pattern or circulation derived from coastal station records. The ice barrier which rises abruptly to several thousand feet behind most of the coastal stations in Greenland affects the observed surface and air-sounding data to such an extent that a much more comprehensive study will be required to establish the lack or the validity of any apparent relationship between the physical parameters measured at the coastal stations and the occurrence of white-outs on the Ice Cap.

Results of Studies at the Ice-Cap Station, Site 2

The frequency and duration of all fogs which reduced visibility to less than one mile have been computed for Site 2 for the period from January 1954 to December 1955. The results, presented in Table 1, show that the summer and fall months have the greatest number of hours of fog and the longest periods of fog. July and August, with mean air temperatures of 19^{0}F and 14^{0}F, are high in both total hours of fog and the duration of continuous fog; however, October and November, with mean air temperatures of -8^{0}F and -22^{0}F, show

Table 1—Frequency and Duration of Fogs
Causing Reduction of Visibility to Less than One Mile at Site 2
January 1954 to December 1955

Month	Amount of Fog (hr)	No. of days on which Fog was Reported	No. of Consecutive Days of Fog*	Average Duration of Fog (hr)	Maximum Duration of Fog in 1 day (hr)	Maximum Duration, Continuous Fog (hr)	Mean air Temperature (F)
January	15.0	3	1	5.0	9	9	-29
February	40.5	8	4	5.1	15	15	-24
March	70.5	11	5	6.4	14	21	-29
April	19.5	4	2	4.9	10	14	-17
May	28.5	7	4	4.1	10	19	2
June	45.0	9	3	5.0	16	18	17
July	75.0	9	3	8.3	16	31	19
August	129.0	17	5	7.6	24	46	14
September	49.5	6	4	8.2	16	26	- 9
October	99.0	15	7	6.6	18	27	- 8
November	103.5	12	4	8.6	21	27	-22
December	48.5	7	4	6.9	16	22	-30

* Fog may have been reported on several consecutive days without being continuous over the period of record.

an incidence and duration of fog almost equal to the summer months.

As shown in Table 2, fog occurred 73% of the time when temperatures were above 29°F. However, within the temperature range of -69°F to +29°F, there was little variation in the frequency of fog. The lowest frequency occurs within the temperature class -39°F to -30°F, which includes the spontaneous nucleation or freezing temperature range for supercooled water droplets. As stated previously, it has been observed on the Ice Cap that crystallization of supercooled fog appears to induce precipitation and clearing of the atmosphere with resulting increase in visibility.

The comparatively high frequency of fog white-out reported within the temperature range of -40°F to -69°F probably may be attributed to the formation of "diamond dust," extremely small ice particles which remain suspended in the air because of lack of sufficient moisture for growth to a size permitting fall-out.

During the summer of 1955, fogs occurred at Site 2 on part or all of each day from 31 July to 4 August, inclusive. They were usually visible on the horizon for one to two hours before arrival. The occurrence of these fogs appeared to be associated with a shift in the wind to the south from the usual southeast or east direction.

The wind rose for Site 2 presented in Fig. 4 demonstrates that there is a definite relationship between wind direction and the occurrence of low visibility. The solid-line wind rose shows that when visibility exceeded one mile, the mean prevailing winds were from the southeast with a strong easterly component. During periods of fog the wind was predominantly from the south as shown by the dotted-line wind rose. For the two-year period of record covered by these wind roses, the wind was in the SE to E octant 67% of the

Table 2—Relation between Air Temperature and Occurrence of Fog at Site 2. January 1954 to March 1956

Temperature Class	Frequency*	Fog Frequency $(100x \frac{f}{F})$**
30 to 39	1	73
20 to 29	10	20
10 to 19	16	18
0 to 9	13	17
- 9 to 0	12	21
-19 to -10	15	12
-29 to -20	13	14
-39 to -30	10	9
-49 to -40	6	15
-59 to -50	3	10
-69 to -60	1	16

*Percent of all observations for 27 months which fell in the indicated temperature class.

**f = frequency of fog within the temperature interval.
F = frequency of air temperatures within this interval.

time when visibility exceeded one mile. When fog was reported the wind was in the S to SE octant 67% of the time. The frequency of wind from the SSW and SW during fogs was twice as great as for periods of no fog.

A similar relationship between wind direction and the occurrence of fog is shown in the wind rose for Site 1, presented in Fig. 5. This station is located at an elevation of 4,500 ft about 200 miles west of Site 2 and north of Thule. At Site 1 about 66% of the periods of low visibility occurred when wind was from the S-SE octant as was found for Site 2. At Site 1, however, about 20% of the periods of low visibility were associated with wind from the N-NE octant while at Site 2 there was almost no wind or fog from that direction. The fogs associated with the northerly winds at Site 1 may be related to the Thule coastal sea fogs.

The association of clear weather or good visibility with an easterly wind at Thule was reported in the 1953 studies on summer fog. At Thule, however,

fogs were more commonly associated with northerly and westerly winds instead of the southerly winds identified with most of the white-outs on the Ice Cap.

A shift in wind direction occurred at both Sites in advance of the fog as shown in Tables 3 and 4. In 167 out of 212 instances of fog at Site 2 over a two year period, the wind shifted clockwise from 3 to 24 hours prior to the onset of fog. At Site 2, there was a shift in wind direction toward the South or the North during the previous 3 to 24 hour period in 75 out of 115 recorded observations of low visibility.

Table 3 Wind Shift Prior to Fog with Visibility of 1 Mile or Less, Site 2. January 1954 to December 1955.

Frequency of Occurrence				
More than 24 hr	12 to 24 hr	6 to 11 hr	3 to 5 hr	Less than 3 hr
6	29	56	82	39
Frequency Percent				
3	14	26	39	18

Note: No record for 1 Sept. to 10 Sept. 1954

Table 4 Wind Shift Prior to Fog with Visibility of 1 Mile or Less, Site 1

Frequency of Occurrence				
More than 24 hr	12 to 24 hr	6 to 11 hr	3 to 5 hr	Less than 3 hr
7	28	26	21	23
Frequency Percent				
7	26	25	20	22

The advection of warm, moist, maritime air from the coastal areas, with uplift onto the cold ice cap, may be associated with the change in wind direction. Winds from the S-SE octant, which occurred with fogs at Sites 1 and 2, probably derived their moisture from Baffin Bay. Winds from the N-NE octant, which accompanied fogs at Site 2, may have picked up moisture from the Kane Basin. The combination of convective lift to elevations above 4500 ft and advective transport from the coast could produce and maintain a fog on the Ice Cap, or a low stratus cloud above the cap, from air that was less than saturated at sea level. It is possible that both fog and low-stratus white-outs which are reported from stations at higher elevations on the Ice Cap when lower stations report unlimited ceiling and visibility are the product of much uplifted maritime air.

A microclimatic study of the conditions associated with a fog white-out which occurred at Site 2 on 1 and 2 August is presented in Fig. 6. The fog was first observed as a cloud bank to the southwest about 1700 hours on 1 August. At 1910 hours the station was engulfed in a dense white-out which persisted until 2000 hours on 2 August. As shown in Fig. 6, air temperature and dewpoint were falling at about 1.5°C per hour prior to the onset of the fog. The long-wave radiation during the four hours preceding the white-out was negative with a maximum loss approaching 0.95 ly/min.[1] One who had not seen the approach of the fog or low clouds from the southwest might conclude from the microclimatic record that the reported white-out was a non-advective, radiation-fog, the product of radiational cooling of the snow surface with the concurrent drop in temperature of the overlying saturated air. The lowering of surface air temperature prior to a summer fog was reported also in the Thule studies (1953).

The air temperature and dewpoint rose rapidly as the fog engulfed the Ice

1. 1 ly (langley) = 1 gm cal/cm^2.

Cap station and net radiation became positive, increasing so rapidly that the gain in heat of 0.5 ly/min from radiation alone might have been expected to disperse the fog. Air temperature increased and the dewpoint rose above the ambient temperature indicating a supersaturated air condition.

The rise in air temperature during the white-out period may be due in part to the advection of a warm air mass but there is no doubt that the absorption of solar radiation at the top of the fog and curtailment of long-wave radiation heat loss from the snow surface by the fog cover contributed largely to the higher air temperatures which persisted during the white-out.

It appears that at this time of year (early August) when the sun is low at night, radiation heat losses from the snow cover may set up conditions favorable to ground-fog formation but the low air temperature and the low absolute humidity which prevail during this period are not conducive to formation of persistent fogs nor to white-outs as dense as those encountered during the period of observation. Although the air was close to saturation during most of the white-out period, air temperatures were mostly below -10°C, a condition not favorable to the production of a dense, persistent radiation fog. The "drying out" action described by Petterssen (1950) which he attributes to the difference in vapor pressure between the water droplets in a supercooled fog and the ice crystals comprising the snow surface would have favored rapid dispersal of the fog if it had been due only to radiational cooling.

The occurrence of summer fog at Thule was reported to be associated with a dewpoint spread of 2° F or less. This is in agreement with Taylor (1917) and George (1940) who have emphasized the importance of dewpoint depression along with air trajectory in the development of procedures for forecasting the formation of fogs. Surface temperatures during the Thule studies were mostly above freezing, frequently being 40° F or more during a fog. On the Ice Cap, at Site 2, temperatures seldom rise to the freezing point. It is difficult to measure the dewpoint at temperatures below freezing with a sling psychrometer, hence a relationship between dewpoint spread and white-out on the ice cap may not be as reliable as for the summer fogs at Thule.

Available records of dry bulb and dewpoint temperatures from Site 2 were analyzed to determine whether a reduction in the dewpoint spread could be detected prior to the onset of a fog white-out. Summaries were made for the two months of April and May when white-outs occur infrequently, for July and August when the very frequent fogs appear to be associated with high ambient temperatures, and for October and November when the white-out condition occurs frequently during periods of very low temperature.

The data in Table 5 show that the extreme variability in the dewpoint depression, as measured at the Ice Cap site, prohibits the use of any apparent narrowing of the dewpoint spread in the development of a forecast scheme for white-out. The standard deviation of the means is almost 50 percent of the average dewpoint depression for any of the selected periods and it is greater than any difference in the dewpoint spread between conditions of good and of poor visibility.

The most impressive phenomenon during the entire 25 hours of white-out covered by Fig. 6 was the comparatively high wind which increased from 5 knots at the start of the white-out to 12 knots during mid-period and slacked off to 8 to 10 knots at the time of clearing. During the period of higher wind velocities, the fog shifted almost momentarily between the supercooled liquid-droplet phase and the ice-crystal phase with both phases frequently coexistent. The colloidal instability associated with coexistence of ice

crystals and supercooled water-droplets actually appears to be a more or less stable condition when high wind velocities produce considerable mechanical turbulence within the fog. The rapid changes in liminal visibility and depth perception associated with this instability increase operational difficulties during white-outs.

Byers (1944) states that an up-slope fog is about the only one that can be maintained in relatively high wind velocities since the more rapidly the air moves up a slope, the faster is the cooling process and the greater the counteraction of any downward transfer of heat by turbulence. Petterssen (1940) points out also that an up-slope wind has a marked effect on fog production. The high wind velocity of 10 to 12 knots at Site 2 during the white-out of 1 to 2 August indicates that an up-slope effect probably contributed both to the formation and the maintenance of the fog.

DISCUSSION

The fog-type white-outs which impose the most serious handicap to air movement and ground transportation on the Greenland Ice Cap appear to be largely the product of warm maritime air which has been lifted several thousand feet and cooled first by adiabatic expansion and further by transport over the cold snow surface. Radiation cooling of the snow surface by long-wave losses prior to the advent of the fog may contribute to the formation of the white-out.

Since a fog white-out usually is preceded and accompanied by winds from the south, whereas prevailing winds are from the southeast or east, it is probable that changes in the upper-air circulation pattern may be related to white-out formation in this part of the Arctic.

Upper-air observations may provide some clues to the formation of white-outs. When combined with surface observations, it may be possible to forecast the occurrence and even the duration of white-out. The stratus-cloud white-out and the fog white-out which are the predominent types in polar regions appear to be of the same origin and it may not be possible to forecast which form will occur. There is no indication that the dewpoint spread, which has been proposed as a basis for forecasting fog at airfields in the temperate zone, can be used to develop a forecast scheme for any form of white-out.

The fact that both the fog- and cloud-type white-outs frequently occur under conditions of very low temperature and low absolute humidity indicates that dispersal of this type of white-out might be accomplished by nuclei seeding or by atmospheric warming such as the FIDO procedure used during World War II. The lack of convective lift and turbulent mixing of air over the broad, flat snow-covered surface during many periods of white-out may prevent satisfactory dispersal by ground-installed equipment of the type used to induce rainfall in the Southwestern States. Wind speeds of 10 knots or more which accompany some white-outs may cause too-rapid recharge of moist air to permit effective dispersal or prevent control of the dispersal to the desired location. However, the overall physical conditions associated with white-outs do appear to justify attempts at modification by seeding the fog or stratus cloud from aircraft, captive balloons, or low-altitude pyrotechnic rockets. Successful modification would produce a "window" through which aircraft could let down to land on air strips in polar regions.

SUMMARY

Limited studies on Arctic white-outs indicate that there are five major conditions producing low visibility. They are:

1. Overcast white-out caused by a continuous cloud cover.
2. Water-fog white-out produced by a supercooled water droplets in the air.
3. Ice-fog white-out produced by ice crystals suspended in the air.
4. Blowing-snow white-out produced by wind-driven, wind-eroded snow.
5. Precipitation white-out produced by falling snow.

The first three types are interrelated and appear to be produced by upslope, convective lifting of warm maritime air and the advective transport of the cooled saturated air over a cold snow field. Radiation heat losses from the snow surface prior to the onset of fog conditions may contribute to a more rapid formation of white-out.

The fact that there is a shift in the prevailing wind direction prior to the development of a white-out indicates that certain changes in upper-air circulation may be associated with white-out formation and duration.

There appears to be reason to believe that white-outs on the Greenland Ice Cap may be forecasted with some degree of reliability.

It is possible that cloud seeding procedures may be used to induce dispersal of some types of white-out over airfields in polar regions.

BIBLIOGRAPHY

Byers, Horace R., (1944) General Meteorology, New York: McGraw-Hill Book Co., First Ed., Ch. XXI.

Church, Howard V. (1946) Correspondence to Editor, Bulletin, American Meteorological Society, vol. 27, p. 613.

Court, Arnold (1949) "Meteorological Data for Little America III," Monthly Weather Review (U.S.), vol. 56, p. 435-437.

8th Weather Squadron, Air Weather Service (1953) "Forecasting Summer Fog at Thule, Greenland," Tech. Memo No. 2 (Unpublished), ASTIA No. 31862.

5th Weather Group, Detachment 24, Air Weather Service (1956) "Fog Study, Thule AB, Greenland," (Unpublished).

George, J. J. (1940) "Fog, Its Causes and Forecasting, with Special Reference to Eastern and Southern United States," Bulletin, American Meteorological Society, vol. 21, p. 135-148; 261-269; 285-291.

Petterssen, E. (1940) Weather Analysis and Forecasting, New York; McGraw-Hill Book Co., First Ed., Ch. II.

Taylor, G. I. (1917) "The Formation of Fog and Mist," Quarterly Journal, Royal Meteorological Society (London), vol. 43, p. 241-268.

Willett, H. C. (1928) "Fog and Haze," Monthly Weather Review (U.S.), vol. 56, p. 435-437.

Fig. 1. A typical clear day on the North Greenland Ice Cap, at an elevation of 7000 ft near 78° N, 55° W, July, 1954.

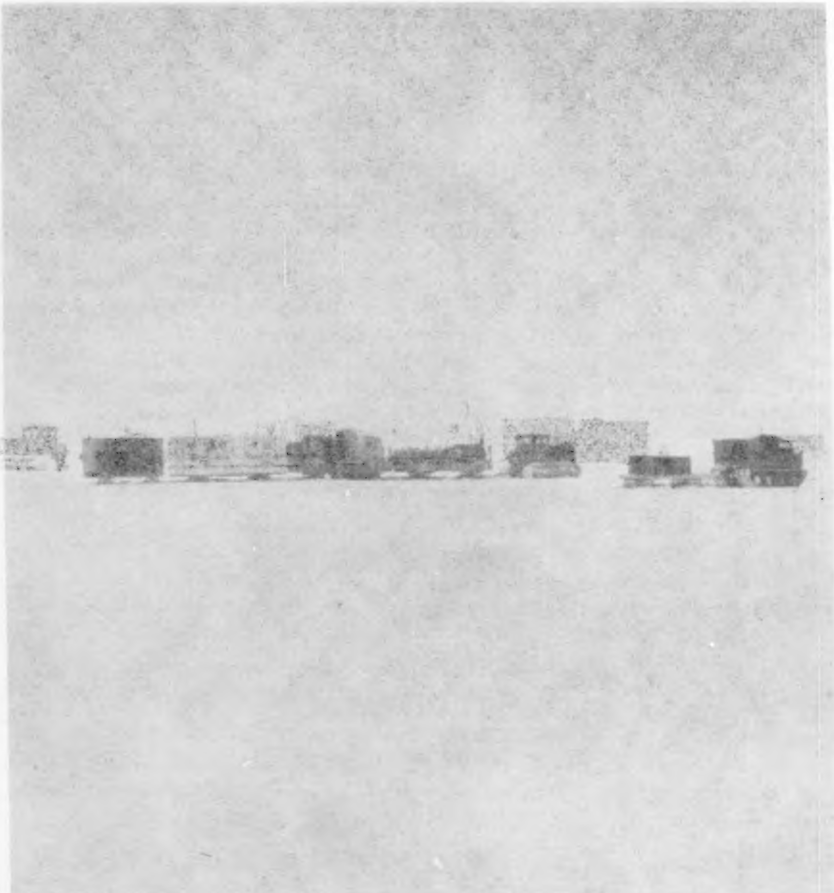

Fig. 2. The development of a water-droplet fog-type white-out on the Ice Cap. Location the same as Fig. 1, July, 1954.

Fig. 3. Typical, overcast white-out conditions. Note total absence of horizon and lack of surface contrast in this photograph. Location the same as Fig. 1.

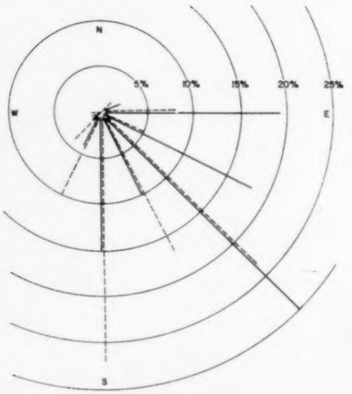

Figure 4. Comparison of wind direction during fog with mean wind direction when visibility was more than 1 mile, Site 2.
—— Mean wind rose with visibility greater than 1 mile, January 1954-December 1955.
----Wind rose January 1954-December 1955 during fog white-out.

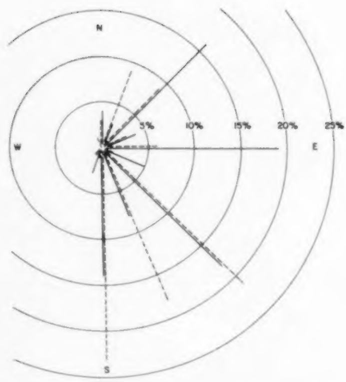

Figure 5. Comparison of wind direction during fog with mean wind direction when visibility was more than 1 mile, Site 1.
—— Mean wind rose with visibility greater than 1 mile, 20 July 1953 to 31 August 1954.
----Wind rose during fog white-out, 20 July 1953 to 31 August 1954.

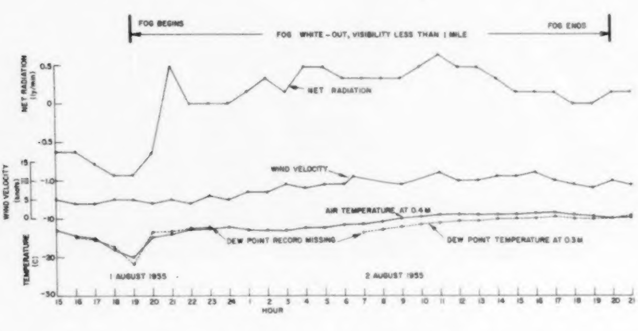

Figure 6. Air temperature, dew point, and net radiation before and after fog, August 1955, Greenland Ice Cap.

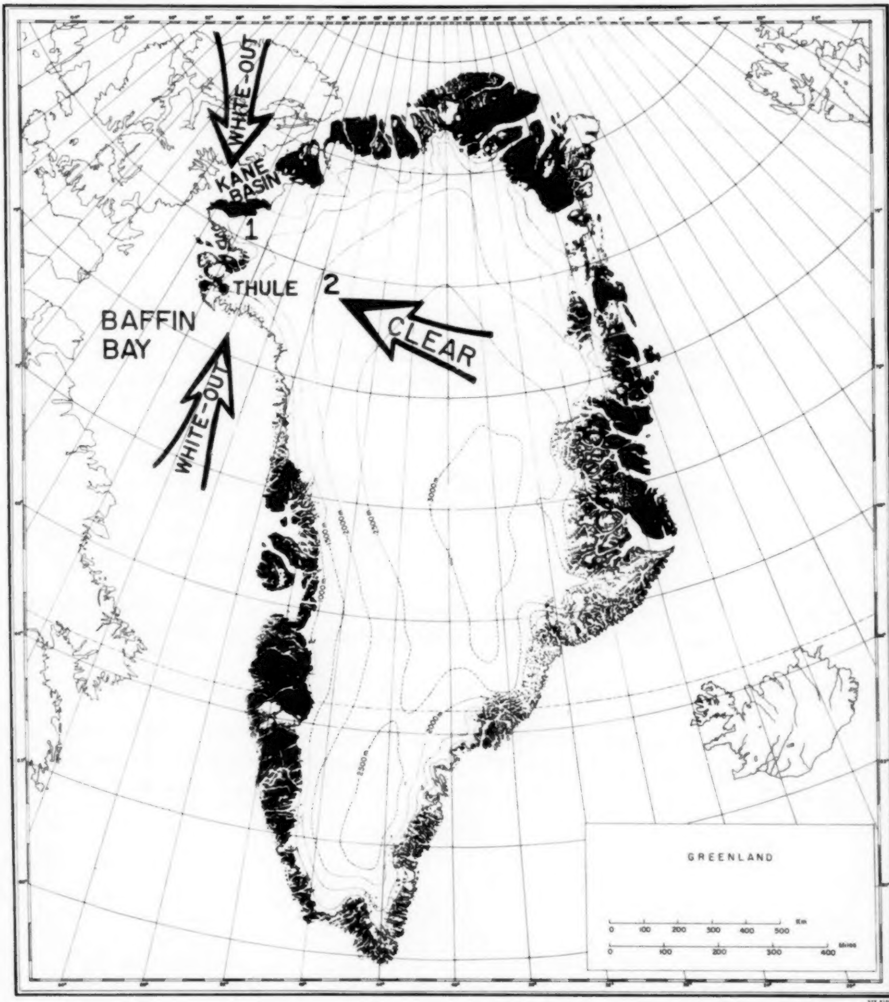

Fig. 7 — Greenland Test Sites 1 and 2.

Journal of the
AIR TRANSPORT DIVISION
Proceedings of the American Society of Civil Engineers

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Discussion of
"COLD REGIONS RESEARCH BY THE U. S. CORPS OF ENGINEERS"

by Robert R. Philippe
(Proc. Paper 1323)

ROBERT F. LEGGET,[1] M. ASCE.—It is perhaps appropriate that a Canadian should open the discussion on this interesting paper. With its immense northern area, Canada is vitally interested in flying in cold regions and there is probably more civilian flying under such conditions in Canada than in any other country in the world. Much of Canada must be classified as a cold region, particularly the Queen Elizabeth Islands as our Arctic archipelago is now known, and the subject matter of this session is therefore of very great interest to Canadians. Flying in northern Canada is the responsibility of the Royal Canadian Air Force, the federal Department of Transport, and a large number of private airline operators, notably Canadian Pacific Air Lines. All these organizations have many experts on their staff who are well versed in the problems of northern flying. The relatively small population of Canada is such that all of us who are concerned in any way with the North work together in order to make the best possible use of all our available human resources. It has been a privilege of members of the staff of the Division of Building Research of the National Research Council of Canada to be closely associated with a number of developments in the North and to have the benefit of close and intimate contact with many of those who are actually responsible for our northern flying operations. As minor trouble-shooters members of the Division have had some direct contact with some of these problems and much of the northern research work upon which the Division is now engaged has direct relevance to the subject matter of this Symposium.

It is clear from Mr. Philippe's paper that much work of great interest, and of potential value far beyond the land of Greenland, has been and is being conducted by the U. S. Corps of Engineers upon this greatest of islands of the northern hemisphere. The fact, however, that Mr. Philippe's paper is by an American author dealing with American military work carried out in the territory of another country places any discussor who comes from yet another country in a position in which one word spoken out of place might create an international incident. Relations between Canada and the United States have been for so long so harmonious that the writer dares not run such a risk. This discussion will be confined to some general comments on Canadian experience in flying in cold regions, which comments have been prompted by and are directly relevant to Mr. Philippe's excellent presentation.

If Canada has made any special contribution in the development of aviation it has surely been in the opening up of its northern territories by pioneer bush flying, the stories of which have already become epics. It was upon the intrepid work of such pioneers in the years before the Second World War that the more recent developments in northern flying have been based.

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Notable among these is the fact that for several years Canadian Pacific Air Lines have been operating steadily and successfully a regular scheduled service from Edmonton to Aklavik on the shores of the Arctic Sea. This regular service is typical of the way in which flying all over northern Canada has developed. That this type of flying is now taken for granted is confirmation of the fact that there are no major outstanding problems today in flying in cold regions, as Mr. Philippe has observed.

It is true that there are difficulties but these are not specifically related to the weather, as such, as is so often imagined. The cold conditions are so continuous that this leads to relatively stable conditions at the altitude at which planes normally fly. Wind is a dominant feature but it is a steady wind and at ground level, generally horizontal, affecting only landing and take-off conditions.

As Mr. Philippe has pointed out there are no basic problems in navigation. In Canada it is considered that this is due in large measure to the outstanding work of W/C Keith R. Greenaway of the Defence Research Board of Canada whose navigational developments will be well known to all concerned with flying in the North. One unusual minor problem is that of "whiting out" due to the glare from ice in a pilot's eyes at low-level flying. This is under study.

The major interest of those reading this will probably be in the civil engineering aspects of transport in cold regions. The following comments are pertinent to this aspect of airfield construction in the North. Apart from those fields that can be built on natural deposits of sand and gravel or solid rock, airfields in the Far North must be built either on compacted snow, on ice, or on permafrost. Each type presents special problems but the chief problem is always that of location. It is safe to say that if experienced civil engineers had been permitted to locate all the airfields and airstrips in northern Canada there would really be few problems today apart from those created by the unusual materials. In some cases, however, airstrips have been located for geographical reasons and this has led to some side difficulties.

Snow compaction will not be discussed here except to note that much practical field experimentation has been done in Canada on snow compaction by a variety of agencies, notably by the Canadian Army in some very extensive trials at Kapuskasing. The opinion of the National Research Council is that such empirical work has really gone about as far as can be expected and that further advances in the field of snow compaction must await a thorough examination, in the laboratory and in the field, of snow as an engineering material.

It has been the practice of light planes flying in northern Canada to use ice on rivers and lakes for landing purposes for many years. This has led to an accumulation of much practical experience which is now available for use and which is steadily being extended as flying develops. Again, however, it is clear that the next advance in this field must come as a result of theoretical laboratory and field studies of the strength of ice with special reference to the conditions under which planes may safely land on ice, the thickness of which is known. It is therefore most appropriate that this Symposium should contain a paper on this very special problem. The Snow, Ice, and Permafrost Research Establishment of the U. S. Corps of Engineers, with which the National Research Council of Canada has been privileged to maintain the closest possible association, is very active in this field. The National Research Council of Canada is working on this problem in a special snow and ice laboratory in Ottawa and, in so far as possible in this as in all other associated fields, the Council is attempting to correlate its work with that of the Corps

of Engineers since there is so much to be done and so few to do it.

Exactly the same comment may be applied to the problems of building airfields on permafrost. It may be fitting to note that so important is permafrost to the economy of the Canadian North that the Division of Building Research maintains a special northern laboratory for permafrost research at Norman Wells, almost on the Arctic Circle. To some extent we are still at the question-asking stage, but know that there are factors about construction in permafrost that are still only improperly understood. For example, while it may be possible to make theoretical calculations about the requisite thickness of base courses over permafrost, it is suspected that part of the problem of the thermal regime of permafrost, particularly during summer months, is linked to evapotranspiration from muskeg. This one factor may have a profound influence on theoretical calculations. One gravel embankment, not more than five feet high, has been stable for over a decade in one of the worst locations known in northwestern Canada. The Council is studying this problem and hopes to extend these studies as more airports are built on poor sites in the Canadian North, in particular at one airport which is going to be built not far from the embankment to which reference has been made.

All the points mentioned in the preceding paragraphs are included in Mr. Philippe's exhaustive treatment of the work of the U. S. Corps of Engineers in Greenland. It has been the writer's intention to make clear that these are international problems taking no cognizance of international boundaries. Even more important is that research into such problems is also international in character, to the extent possible. It is for this reason that these few comments have been presented as an introduction to the subsequent discussion that will be as interesting as it will prove to be profitable.

Discussion of
"TESTING OF A COMPACTED SNOW RUNWAY"

by James A. Bender
(Proc. Paper 1324)

DENO G. PAPAS,[1] J.M. ASCE.—At the outset it must be understood that we are discussing a relatively new field of engineering. We are discussing the results obtained from a single operation and an attempt has been made to correlate these findings with the results obtained from small-scale laboratory experiments whose conditions, for the most part, were in no way similar to those existing during and after the runway pavement in question was constructed. These facts are brought out in order to instill some semblance of caution and to forestall jumping to conclusions. That a few aircraft landed successfully does not mean that a satisfactory method of construction has been devised. In further justification of this attitude, it should be pointed out that the conclusion, "the strip could support certain aircraft," was based primarily on the decision of the Project Engineer who reached this conclusion after consideration of the performance of the snow pavement when subjected to tests with a load-test cart.

In presenting this discussion, no attempt will be made to evaluate the test results. Mr. Bender has expressed the feelings of all who are closely associated with the problem of snow compaction when he stated that "additional theoretical and field work is necessary." It is the writer's impression that it is much too early to state that the Rammsonde is an adequate test instrument.

Before entering into a discussion of the test methods, it must be stressed that the use of snow as a runway-construction material is a relatively new field. The term "design criteria" is usually referred to as that procedure which must be followed in the construction operation of a snow pavement which will provide the required bearing or traffic capacity. "Methods of testing" comprises investigations designed to determine whether or not the snow pavement was constructed in accordance with specifications previously derived to meet the design-load requirements.

Taking into consideration the fact that there is yet much to be explored in the field of snow as a construction material, the smallscale tests mentioned in the author's report are a vital and necessary step in conquering this new field. However, there seems to be some confusion in the report as to the difference between tests required during the development of design criteria and those required for construction control. The simple "in-place" tests are confined to a description of the Rammsonde tests.

By way of explanation, it is pointed out that the readings obtained with the Rammsonde are obtained by loading a 1-in.-diameter area. Yet it is suggested that such readings may be used to predict the probable performance of a pavement intended to support dual-wheel loads up to 80,000 lb. and loaded areas up to 300 sq. in. The Rammsonde produces an index number, which to

1. Engr., Research and Development Labs., Fort Belvoir, Va.

be of any use, must be correlated with temperature, density, grain size, age, processing procedure, and actual traffic tests, to name a few of the presently-known determining factors.

It can readily be envisioned that in compacting snow, the ideal pavement to be produced would be one of ice. The Rammsonde was developed for measuring the hardness of undisturbed snow. In such snow it would be possible to obtain a 36-in. profile in 5 minutes. However, in the writer's experience in the summer of 1956 in obtaining a profile of the runway pavement being discussed, it took up to half an hour to measure the top four inches. It can be considered that, in that half hour of pounding, the characteristics of the affected snow changed considerably for the better; the high plastic and low elastic characteristics allowing the snow to remold itself. Therefore, with a density increase, time-of-hardening increase, and a temperature decrease, the effectiveness of the Rammsonde decreased.

In view of the shortcomings of the Rammsonde test, the writer believes this test is applicable to methods of test for construction control. The only reliable measurements from which design criteria could be developed are density, temperature, processed grain-size, and bearing capacity as determined from traffic tests with live-wheel loads. The latter must be done with a rubber-tired load cart.

The tests made to determine the unconfined compressive strength of snow-pavement samples are a good start in the development of methods of testing. The values obtained are indicative only of the probable strengths which may be uniformly attained in a snow pavement. The wide range of values quoted by the author indicates the erratic performance of the processing equipment. The writer wishes to call attention to the matter of the rate of application of load. Previous tests, using similar samples, have indicated that more consistent results were obtained when the rate of load application was increased appreciably. The increase in rate of application overcomes the viscous characteristics of snow under load and provides a more realistic representation of the dynamic loading to which the snow pavement will be subjected by aircraft. Again, since snow has very slight, if any, elastic characteristics under rapidly-applied loads, the writer agrees with the author's statement that some questions exist whether a value of Young's modulus can be determined from a stress-strain curve for snow. This raises the question, "What are the characteristics which negate Young's modulus and how they can be measured in terms which can be correlated with the behavior of a snow pavement under traffic?"

The shear strength of the snow, particularly in the top layer of the pavement, is probably the most critical end product with which the vehicle driver must content. The break-throughs under large-scale testing were, in reality, shear failures produced by a slow-moving load. It appears that a given snow when confined will support a considerably greater static load than when unconfined. In the latter condition, the loaded area increases when a shear failure occurs; this presupposes further shear resistance is developed at greater depth in the pavement. The actual manner in which load is distributed in snow is not completely understood, nor will it be until further research is done.

In his consideration of the conditions under which the aircraft landings were made, the author did not report that some 12 to 18 in. of new snow had been rolled and leveled on the processed pavement prior to the landings. Based on previous experience, it is estimated that the density of this rolled

snow was between 0.5 and 0.55, similar to the 5 to 40 in.-compacted subgrade.

It is the writer's opinion that, at the present time, the only reliable way of determining trafficability of a snow runway is by the use of a load-test cart. The load cart is adequate for determining whether or not the pavement will support the aircraft. The Rammsonde was designed primarily for testing undisturbed snow. When used on highly-compacted and aged snow the Rammsonde becomes highly inefficient. The Rammsonde index number is of little value without knowledge of the density profile, temperature, age-hardening of the pavement, method and depth of processing, and grain size of the snow. The many combinations of these variables render the Rammsonde index number invalid for use as a design criterion.

Discussion of
"AIRCRAFT OPERATIONS ON FLOATING ICE SHEETS"

by S. Russell Stearns
(Proc. Paper 1325)

LOUIS DeGOES.*—A knowledge of ice as an engineering material and an understanding of it from the engineering viewpoint are paramount to successful aircraft operations in the Far North. The recent air operations to establish the Distant Early Warning (DEW) line would have been impossible without the invaluable contributions of the ice scientists and engineers of the Snow, Ice, and Permafrost Research Establishment (SIPRE), Corps of Engineers, U. S. Army. As Professor Stearns, with Dr. Assur and Mr. Bender, spearheaded the initial ice surveys and provided the technical assistance so vital to the success of the operations, it is highly fitting that he should be selected to present the foregoing paper.

That part of the author's paper dealing with aircraft operations of floating ice sheets is of particular interest to those engaged in Arctic military air operations. As it deals primarily with the engineering aspects of operations on ice, it may not be out of place here to comment on the strategic and economic importance of aircraft operations on ice, and to indicate some of the problem areas in which help from the engineering fraternity is critically needed, and can be of the greatest value.

The arctic offers tremendous opportunities for aircraft operations, provided ice and snow can be used for runways. It is now known that airfields can be built on pack ice, on the Greenland and other ice caps, on fast ice in bays, fiords, lagoons, along coasts, and finally in the many lakes and rivers. How much advantage will be taken of these possibilities and opportunities depends on the role given ice airfields in our concept of Arctic air operations.(1) How well the potentialities of the ice airfields may be exploited depends largely on the effort invested in understanding the Arctic environment and in meeting the engineering challenges it presents.

The bush pilot has become the Marco Polo of the North. Men who have never seen an automobile accept the airplane with the same familiar appreciation as they do the dog team. Yet military aviation has been hesitant in exploiting its capabilities in the Arctic. Operating techniques have been slow to evolve. New tactical concepts adapted to the Arctic environment have received little attention. This is not surprising when it is considered that the two desperate world wars, since the introduction of the airplane, have been fought almost wholly outside the Arctic regions.

The elaborate defensive systems and bases required to support conventional military operations today are expensive, vulnerable, and have little or no recuperative potential in the face of atomic weapons. A single fighter can deliver a devastating blow with atomic weapons and reduce a large and remote military base to a smoking liability. When we consider the expansive ice and

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snow areas over which our air power must be effective, it is clear that we must exploit to the utmost whatever natural advantages the Arctic offers.

Vast, unpopulated Arctic areas afford exceptional opportunities for camouflage, concealment, and dispersal of activities. Except for a few weeks in the summer, surface temperatures are below freezing. Low temperatures create new problems in lubrication and plague the airman with hydraulic and fuel leaks. On the other hand, snow and ice have definite advantages as engineering materials. Thanks to frigid temperatures and an inexhaustible supply of fresh and sea water, the water pump replaces the concrete mixer for construction, maintenance, and repair of ice runways.

In the past ice airstrips have been used mainly for support and rescue activities. In the future it is conceivable that small tactical air teams may be able to carry out sustained operations from these temporary runways. The basic unit might be built around the all-weather fighter as an atomic-bomb delivery vehicle, supported by long-range air transports or by submarines. Such a widely dispersed force, able to operate anywhere in the Arctic, would possess unparalleled destructive capability, and would be relatively invulnerable to countermeasures, as it could fade away into the trackless expanses of the great Arctic desert as easily as an Arab in the Sahara. The weapon thus forged would be an economical one by modern standards and would advance our offensive capability to the very shores of Asia.

The cost of a permanent concrete runway in the Arctic is roughly 600 times that of preparing a comparable natural-ice runway. The runway at Thule Air Base, Greenland cost $12,000,000; Goose Air Base, Labrador—$11,000,000. The cost of preparing a comparable runway of natural ice is estimated to be from $5,000 to $20,000, depending on the amount of snow removal necessary. True, the operational season of ice runways is somewhat limited; however, in places such as the Greenland Ice Cap, on ice islands, and on shelf ice, ice runways may be operational throughout the year.(2)

Not only the military, but civil air carriers as well, have recently shown lively interest in Arctic air activities. The exploits of the Canadian civil air fleet in providing logistical support to the DEW Line are well known. Although they flew aircraft much lighter than the USAF C-124's, the Canadian pilots made innumerable successful landings on ice, snow, and gravel surfaces, many of them unprepared beforehand. Scandinavian Airlines System presently flies one trip daily in each direction from Copenhagen to Los Angeles, with stops at Sondre Stromfjord, Greenland and Edmonton, Canada.(3) They are also planning scheduled trips in January 1957 from Copenhagen to Tokyo, overflying the North Pole and making one refueling stop at Fairbanks, Alaska. It may not be surprising if they advertise a brief stop at the North Pole as an added inducement to passengers. Rumors of trans-Antarctic civil air routes from South American to Australia are now being heard.

The air operations establishing the DEW Line demonstrated spectacularly the profitable employment of ice airfields. The DEW Line stretches more than 2,000 miles from Alaska eastward to Baffin Island. In the period 10 March to 26 May 1955 (2 1/2 months), C-124 aircraft of the 18th Air Force (TAC) flew 932 sorties and airlifted 18,000 tons of cargo to forward bases.(4) Most of the cargo was delivered at DEW Line sites that, at the time, were little more than geographic coordinates. More than 700 landings were made on 28 ice runways, 18 of them on sea ice and 10 on fresh ice.

Within 30 days from the time the 18th Air Force first learned they were to participate in the operation, a C-124 aircraft weighing 168,000 pounds

landed on the first ice airstrip. Early apprehension of landing such heavy aircraft on ice vanished soon after the first landings, and the airlift phase of the DEW Line operation achieved successes far beyond expectations. Airlift to ice airstrips continued throughout the 1956 ice season, and plans are new in progress for 1957.

One of the main stumbling blocks in developing operating knowhow and tactical doctrine for Arctic air operations is the problem of logistics. The large size and complexity of military aircraft of today demand complex support and maintenance facilities. New and more efficient techniques for logistical support in the Arctic must be developed. The difficulties are many and complicated, but by applying present-day technology intensively to the problems of Arctic logistics most, if not all, of the seemingly insurmountable obstacles can be overcome. Imagination and resourcefulness, combined with a spirit of "can-do," will pay rich dividends.

Ice as an Engineering Material

As the author has pointed out, in the design of steel or concrete structures, one deals with engineering materials whose mechanical properties are fairly well known, or may be safely predicted. Some control over their manufacture may be exercised and certain particularly-desirable properties can be produced.

In the formation of natural ice, Mother Nature is in complete charge of quality control, and she provides a variable material which reflects her ever-changing moods. The quality and thickness of ice may vary widely from year to year in the same geographic locality, and even more so in different areas.

Forecasts of times and rates of ice formation and disintegration are reduced to educated guesses in the light of the meager geophysical data available for the Arctic. Despite this handicap, forecasts of ice conditions based on techniques established by SIPRE were very effective along the DEW Line. On the average, dependable forecasts were made for the beginning of the operational season a month in advance; similar forecasts for the end of the operational season were made five days in advance.(5)

Ice as an engineering material has been likened to soil. Unlike natural ice, the bearing strength of soil may be influenced by controlling its grain-size distribution, moisture content, and compaction. Many of the same climatic and physical agencies at work in soil sedimentation also affect the formation of natural ice. Air temperatures, amount, depth, and duration of snowfall, winds, currents, waves, storms, hydrography, warm ground waters, erosion, metamorphosis of snow to ice, animals (seals), and organic matter (seaweed) all play their part in the life history of natural ice and thereby affect its physical properties. As a result, natural ice is not the homogeneous, isotropic, elastic material one would like to use for building runways. Even ice manufactured artificially under controlled conditions may vary widely in its properties.

Natural ice has been described as a highly-viscous material having the characteristics of a solid.(6) Ice may fracture like any brittle material, or it may flow and gradually deform, depending upon the intensity and distribution of stress, the amount and rate of loading, its structure, quality, temperature, and whether or not it is afloat.

Present ice-thickness criteria are based on the theory of elasticity, with

allowances for such variables as temperature, quality, and degree of risk to be assumed. However, the proportional limit of the stress-strain curve for ice is reported to be of the order of 20 to 25 psi or even less. Ice at high static loads deforms at a steady rate; the higher the stress the higher the rate. Floating ice sheets are often stressed far beyond their proportional limits when supporting heavy aircraft. Under these conditions, theoretical stress analysis methods using the theory of elasticity become no longer altogether applicable, and other factors must be considered.

Referring to the stress-strain curve, a number of questions arise. These are:

1. What is the relationship between the formation of the first ice crack and the elastic limit? Where does the first crack appear on the stress-strain curve?

2. What is the shape of the stress-strain curve between the elastic limit (P) and ultimate breakthrough (2.5P)? Can the factor of time be placed on such a curve to show progressive creep induced by prolonged loading, in view of the fact that military aircraft loads on ice airstrips usually exceed the elastic limit?

3. What are the relationships between ice thickness, load-influence radius, and duration of parking? Can this information be made readily available to users without requiring frequent deflection measurements and ice observations during marginal ice and other unfavorable working conditions? (Preflight requirements in very low temperatures, problems of aircraft maintenance and supply, low ceilings, and low visibility may all combine to prevent proper spacing of scheduled aircraft arrivals at ice airstrips. Aircraft saturation may be so uncontrollable on some airstrips that both aircraft and offloaded cargo have to remain at the same spots for prolonged periods of time).

4. What effect does the radius of the circle of load application (a) have on ice behavior after the first crack forms?

5. How much do temperature-induced stresses (prestresses) affect the first cracking? Are these prestresses measurable?

Considerable progress in determining the bearing strength of ice has been made in recent years, accelerated by DEW Line experiences. Refinements in determining the bearing capacities of ice now permit operations on surfaces previously considered submarginal. As an example, since 1947 the Arctic Construction and Frost Effects Laboratory and SIPRE have reduced their estimates of the sea-ice thickness required for unrestricted operations below 10^{o}F by the C-124 aircraft from 97 to 54 in., a decrease of 43 in., or nearly one-half.

Duration of Operational Season

The duration of the operational season of ice surfaces is of considerable interest to the Air Force. Though they cost very little to prepare, ice airstrips have the serious disadvantage of being usable only during a somewhat limited and restricted season. The durability of ice surfaces depends mainly on freezing conditions, and is affected by temperatures, snow cover, wind, radiation, ice type, and ice thickness.[7]

Along the DEW Line, the season of usable ice for C-124 aircraft extends from about late February to early June. Farther north on such perennial ice features as ice caps, shelf ice, and possible fiord and pack ice, runways may be made operational throughout the year if proper techniques and equipment can be developed to cope with surface melt water and surface ice deterioration during the few weeks of summer thaw. As the author has pointed out, surface softening and ponding of melt water may sometimes curb operations severely, even before the combination of thickness, temperature, and strength dictate the termination of operations.

The climate, and hence the ice-runway operational season, varies considerably throughout the Arctic. The North American and Greenland Arctic together encompass an area larger than the United States and include a comparable variation in such climatic phenomena as temperature, snowfall, snow cover, wind, and solar radiation, all of which affect the growth and disintegration of ice. Ice conditions at different sports along the DEW Line no more resemble each other or those elsewhere in the Arctic than the climate in Pittsburgh, Pennsylvania resembles that at Portland, Maine, Portland, Oregon, Death Valley, California or Miami, Florida.

Curves for the natural growth of sea ice in the Central Canadian Arctic between latitudes 76°N and 64°N show the following trends:(8)

1. Freezeup starts about mid-October.
2. The first 10 in. of ice forms in approximately 10 days, averaging about 1 in. per day.
3. Ice thicknesses increase gradually at a rate of approximately 1/2 in. per day until late March.
4. Curves form plateaus during April and May, suggesting a balance between ice accretion and ablation.
5. In late May and June when air temperatures exceed +10° to +20°F, ablation and disintegration take place rapidly.

Close examination of the ice-growth curves shows that the 54 in. required for unrestricted C-124 aircraft operations is attained by late February or early March, approximately 4 months after the initial freezeup. Disintegration takes place in the late May or early June, narrowing the operational season of C-124 aircraft to 3 to 4 months.

What can be done to help nature accelerate the rate of ice growth after the initial freezeup in order to hasten the start of the operational season? To what extent can nature be outwitted by delaying ice deterioration at the end of the season?

After the first freezeup, the rate of ice accretion may be accelerated by artificial flooding, and in doing so some measure of quality control may be exercised. Natural ice usually grows below the surface at the water-ice contact, where temperatures are always at or near freezing. The warming effect of water and the insulation provided by the overlying ice and snow result in a lower rate of ice accretion than on the upper surface where air temperatures may be considerably below freezing.

After freezeup, artificial flooding of the upper ice surface by pumping will hasten ice accretion, the rate depending on surface air temperatures and the depth of flood-water increments. By starting flooding operations the moment the natural ice is thick enough to support light-weight flooding equipment,

thicknesses can be increased as much as 2 in. per day, and the start of the operational season advanced as much as 3 months. Building up the ice surface in 1-in. increments daily will advance the operational season by 2 months. Construction of ice runways by artificial flooding has many possibilities and is certainly worth investigating further.

Snow cover has an insulating effect that retards the rate of ice growth. The degree of insulation depends on snow depth and snow density. Sea ice was observed to grow 72 in. under a 4-in. snow cover and to only 54 in. under 24 in. of snow, with conditions otherwise identical.(9) Sea ice bare of snow was observed to grow almost half again as fast as it did under 6 ft. of snow.

On a slightly sheltered lake at $0^{o}F$ air temperature, SIPRE estimates that ice covered by 4 in. of snow at density 0.25 will require 29 days to grow from 26 to 32 in.(10) When the same snow cover is compacted to a density of 0.50, only 13 days are required for the same ice growth, less than one-half as much time. These examples demonstrate that snow removal and snow compaction hasten ice growth and the corresponding start of the operational season.

The possibilities of delaying ice disintegration toward the end of the operational season do not appear as promising as those for advancing its start. Natural-ice history curves indicate comparatively rapid ice disintegration and ablation with warming temperatures. A 2- to 3-in. layer of compacted snow delays ice disintegration during rapid temperature changes in early spring, improves traction, and does not seriously retard ice growth. Immediate drainage of ponded melt-water may lessen the rate of ice disintegration and erosion. Research on the use of aluminum powder and aluminum foil to retard ice disintegration and ablation is now in progress.(11)

Field Determination of Ice Conditions

Two procedures have been used in conducting initial ice surveys at uninhabited sites. One method is to keep engines running during ice surveys. Experience shows that when engines of aircraft now used for ice surveys (SC-47 aircraft) stop running in very cold temperatures (below $-30^{o}F$), the probability of malfunction rises sharply. Solidification of oil and hydraulic fluids causes sticky brakes, fractured oil coolers, and makes instrument readings undependable. The other procedure is to off-load ice-survey teams, proceed to a main base, and return later for the ice teams. Poor flying weather and aircraft maintenance difficulties often result in stranding the teams. Hence it is important to develop techniques and equipment that will shorten initial ice surveys and permit a minimum of time on the ground.

Determinations of ice thickness and flexure tests of sea ice require the most time. On the 1955 DEW Line, the ice survey teams chipped ice-thickness test holes 12 in. in diameter by hand with chisels, spoons, and shovels. It took four men from 2 to 4 hours to dig 4 holes through ice up to 105 in. thick. It took 3 men from 1 to 2 days to make beam-flexure and salinity tests of sea ice.

In the 1956 DEW Line ice tests, holes for checking the thickness were made with a 1-in. hand drill designed by SIPRE.(12) Needless to say, progress was much faster in most instances. At $-42^{o}F$ two men drilled 13 holes in 60 in. of sea ice in one hour of working time. Drilling through sea ice posed no problems at the temperatures encountered. Above $-20^{o}F$ they

drilled 6 ft. of lake ice in 10 minutes. At air temperatures below -50^{o}F, the drill would not function properly in fresh ice and the holes had to be chipped by hand tools. Some experimenting was necessary to determine the best techniques for using the drill, which SIPRE is continuing to develop. In a few cases methyl alcohol (aircraft de-icing fluid) poured into the drill hole improved drill action considerably, with much less adfreezing. A 3-in. diameter ice-coring auger operated manually has also been developed and is being further refined. It provides an excellent means of obtaining core samples for studying ice structure. The Air Force Cambridge Research Center is developing an airborne seismic indicator to measure ice thickness, which may permit measurements of remote unsurveyed areas from the air.

Airfield Preparation, Maintenance, and Repair

Most of the equipment and time needed to prepare ice airfields are spent on removing or compacting snow. Snow removal in the Far North often takes much less effort than at such U. S. home bases as Ellsworth AFB, South Dakota and Loring AFB, Maine, where snowfall is greater than it is in the Arctic.

A lesser problem is the necessary leveling and smoothing of irregularities on ice surfaces. Whereas on land this requires cut and fill construction, on ice it can be accomplished simply by flooding. All cracks must be located, marked, and healed. Material for construction and repair is essentially water, found everywhere locally in its various forms.

High snowbanks on runway shoulders, overruns, and approach zones have to be avoided. They are not only safety hazards, but cause excessive drifting in their lees, place additional strain on the ice, and sometime cause ice runways to crown and crack. In 1955 DEW Line operations, two C-124 accidents occurred on ice strips. Both accidents were attributed mainly to high snowbanks at approach ends of airstrips, with poor visibility, gusty winds, and lack of approach markers as contributing factors.

During the summer thaw, generally in July and August, ice surfaces become soft and ablation occurs. Melt water ponded in depressions causes ice erosion, soft spots, pot holes, water-splash damage to aircraft, and generally hampers aircraft ground operations. Aircraft wheels may form shallow ruts on disintegrating ice surfaces, and cause depressions during prolonged parking. Melt water may be controlled by judicious site selection and by building up runways and aprons with artificial flooding and freezing. Proper grading may drain melt water into collecting basins, from which the same pumps and other equipment used for flooding may pump it a safe distance from the airfield.

Airfield Marking

More effective and practical methods for marking ice and snow airfields need to be developed. Opinions differ widely on the subject, which is particularly important because most of these airfields lack air navigational aids, and most approaches and landings must be made visually. Poor runway markings were partly to blame for the two C-124 accidents in the 1955 DEW Line airlift.

Visibility problems are intensified on snow and ice. Illusions of distance

in the clear air and the lack of contrasting, easily-observable terrain features hamper the pilot's depth perception and orientation. Airfield markings must compensate for these deficiencies by furnishing contrast with the uniform snow blanket, especially during landings.

Artic weather creates flying hazards not found in more southerly latitudes. One of the worst of these is the phenomenon known as "whiteout."(13) In a whiteout no shadows are visible, the horizon is indistinguishable, and only dark objects can be seen. Pilots experiencing it have described the sensation as "flying in a sea of milk." Several aircraft flying in whiteouts have landed unintentionally on the Greenland Ice Cap.

Requirements for marking austere airstrips are:

1. Markings must afford pilots the necessary orientation, depth perceptions, and show the wind direction.

2. Approaches, runways, and overruns must be plainly marked, and dangerous obstructions to low-flying aircraft clearly indicated.

3. The marking system must be simple and require as little effort as possible to install and maintain. Runway lighting systems for night operations must be light in weight and transportable by air.

4. Logistic requirements for austere operations demand that materials available locally be used for markings whenever possible. Below the tree line evergreen trees have been used effectively. It is not practical to fly trees to distant strips far north of the tree line. At many DEW Line fields empty fuel drums were employed successfully for the purpose. However, no completely satisfactory and acceptable method for marking austere ice and snow runways has yet been devised, and the problem invites further study and testing.

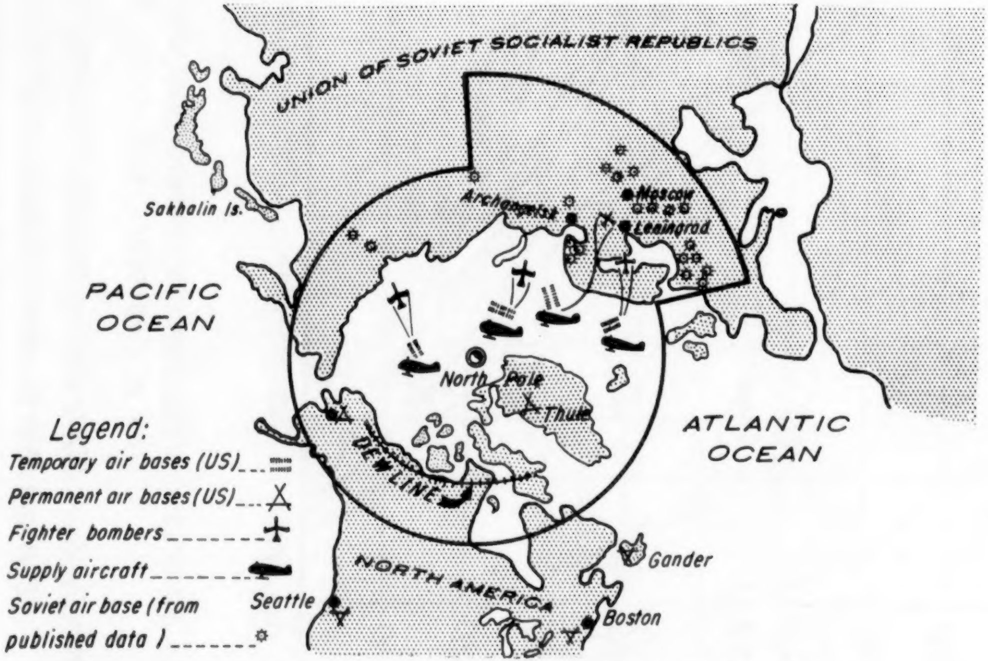
SUMMARY

Successful aircraft operations on ice surfaces demand constant vigilance, alertness, imagination, ingenuity, resourcefulness, and an elementary knowledge of ice physics. Its heterogeneity and dynamic character stamp ice as a tricky engineering material. The operational season of ice runways, unlike that of concrete runways, is usually limited and depends largely on daily mean temperatures and efforts exerted toward snow control, artificial flooding, and the use of additives that retard ice disintegration.

Constructing ice airfields requires considerably less effort in time, equipment, materials, and money than their concrete and asphalt counterparts in the Arctic.

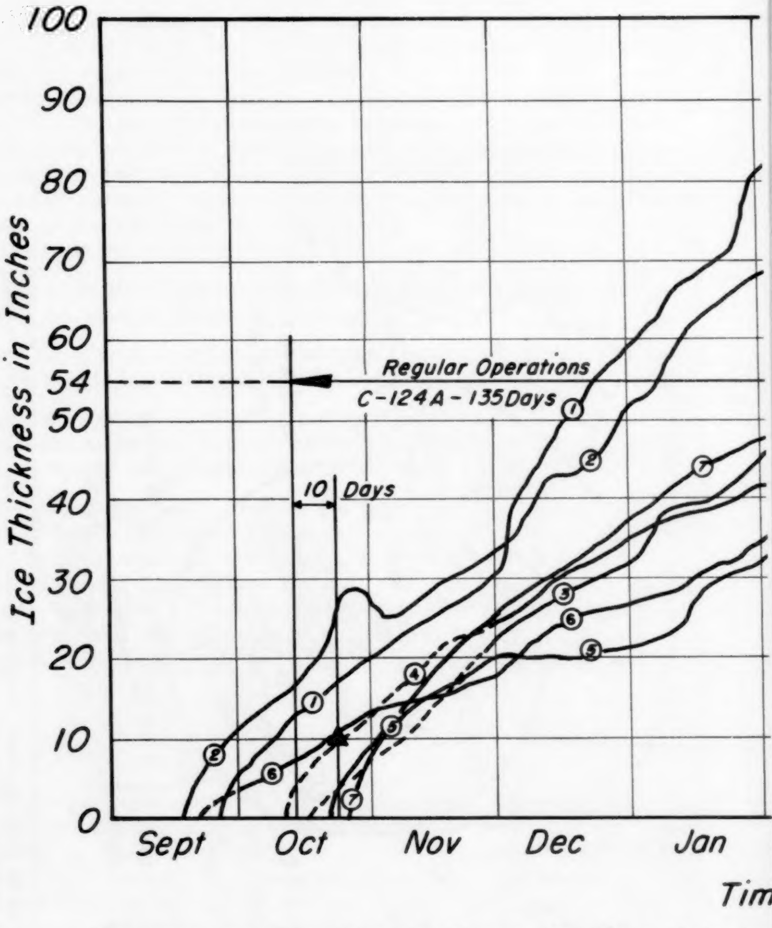
Snow removal and control appear to be the greatest maintenance problems, but are no greater than those encountered at fixed Arctic air bases. Repairs consist of smoothing minor irregularities of ice surfaces and filling fractures with slush or water. During the warmer months, surface melt water poses maintenance problems. Melt water must be controlled to reduce ice erosion and water-splash damage to aircraft during landings and takeoffs. Draining and pumping may be used to control melt water.

The role that ice airfields will play in future Arctic military air operations depends on the degree to which the geophysicist, cryologist, and engineer can solve problems of ice-runway strength, durability, testing, marking, and construction.



This map shows the geographical advantage offered the United States over the U.S.S.R. in vulnerability from the polar air route. Rimming the Russian shore of the Arctic Ocean are many industrial targets and, more important, most of the reported bases of Soviet long-range aircraft capable of carrying the atomic bomb. Only our perimeter bases in Alaska, Newfoundland, and Iceland are comparably exposed, the heart of SAC being protected to the north by some 2000 miles of land.

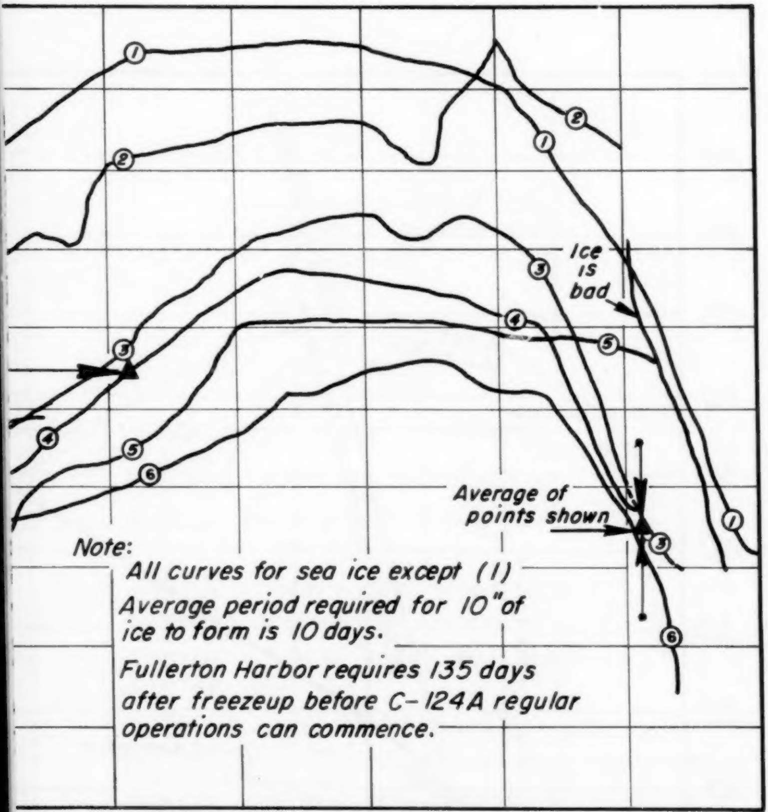
Fig. 1



Source: ACFEL, Report of Investigations, Constru
Corps of Engineers, U.S. Army, May

Curve: (1) River Clyde, Baffin Islands, Fresh Ice, (70°N
(2) Winter Harbor, Melville Island (67°N)
(3) Fullerton Harbour, Hudson Bay (64°N)
(4) Fullerton Harbour, Hudson Bay (64°N)

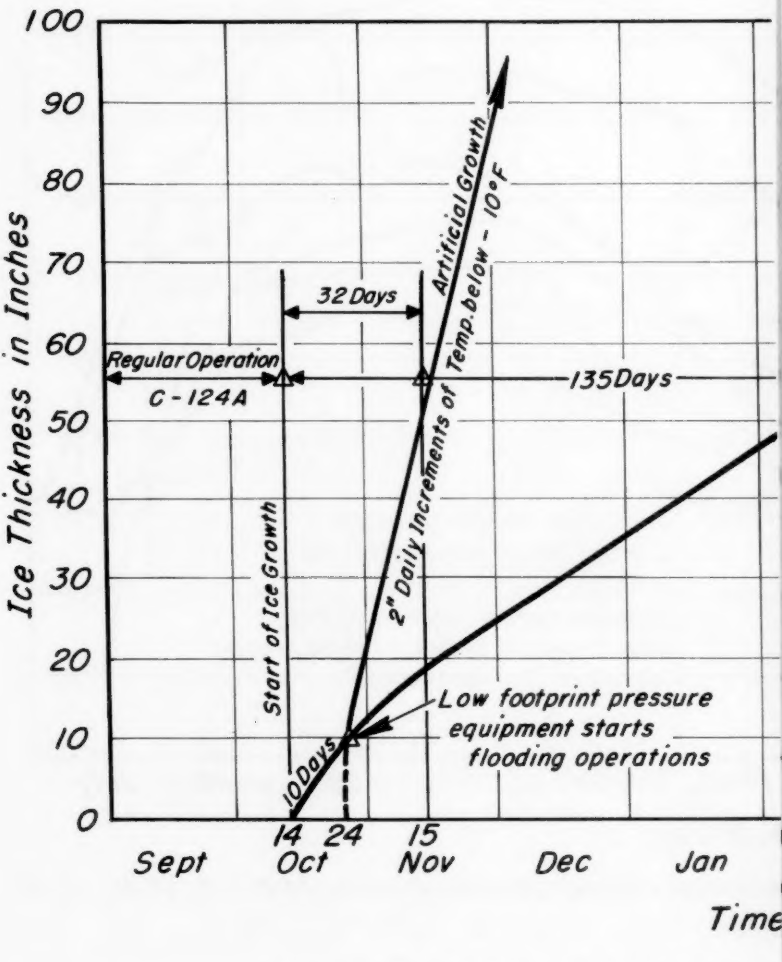
Fig. 2 OBSERVED RATES OF N



tion and Maintenance of Airdromes on Ice, 1946–1948.
948.

(5) Albert Harbour, Pond Inlet, Baffin Island (73°N)
(6) Arctic Bay, Baffin Island (73°N)
(7) Thule, Greenland (76°N)

ATURAL SEA ICE ACCRETION.



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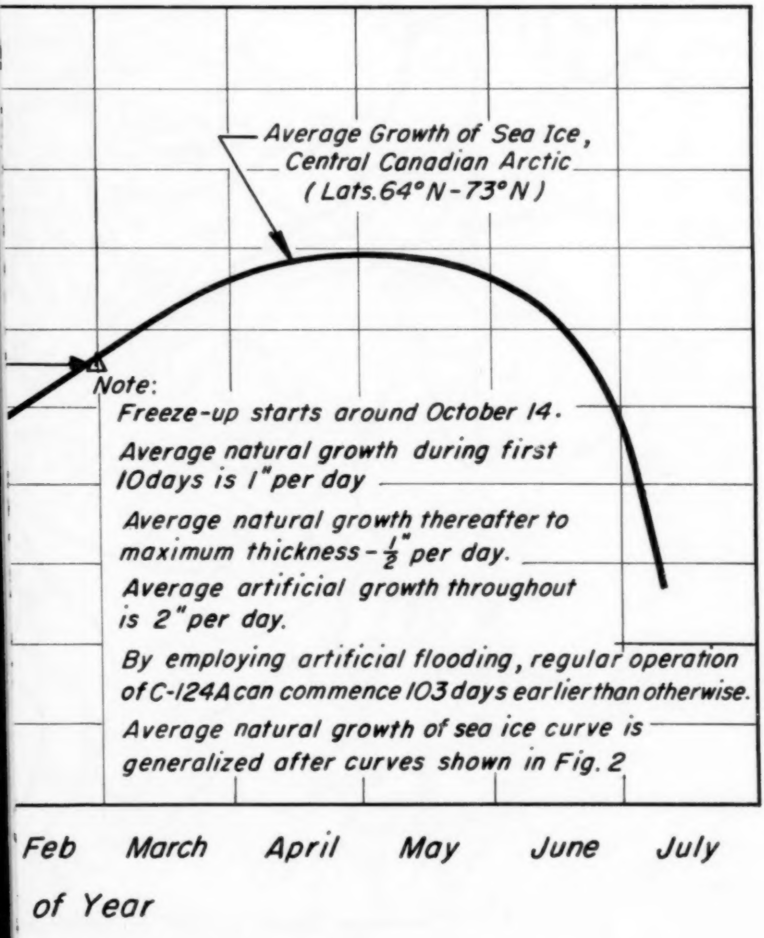

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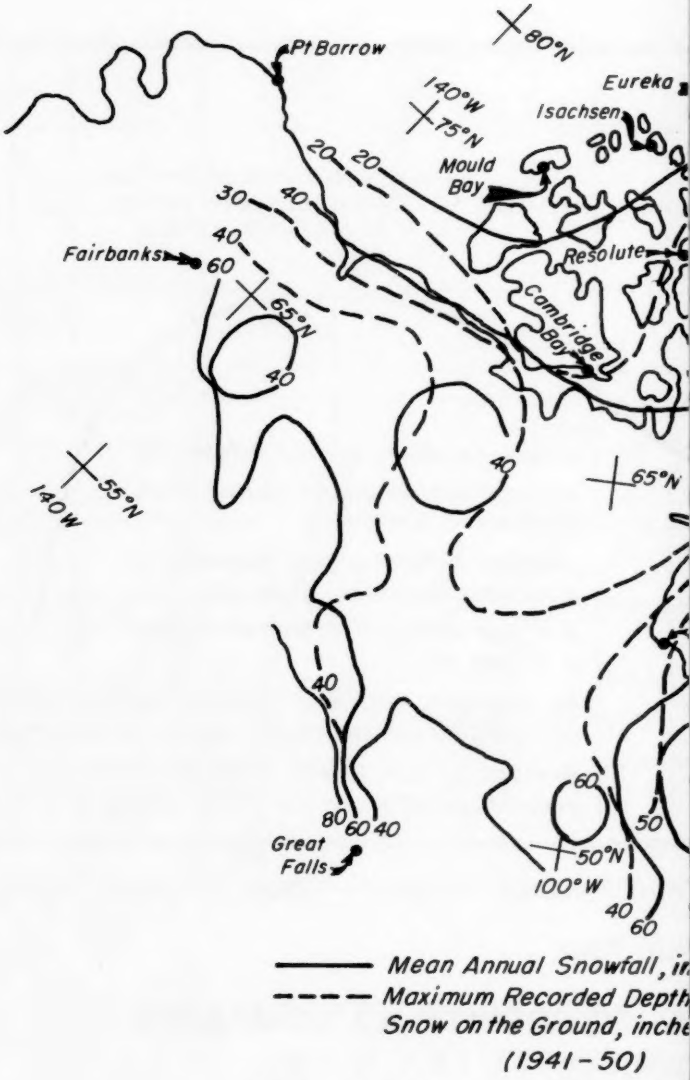

<u>Ref:</u> Climatological Atlas of Canada, Canadian Depa
of Transport, (Morley K Thomas), Dec. 1953.

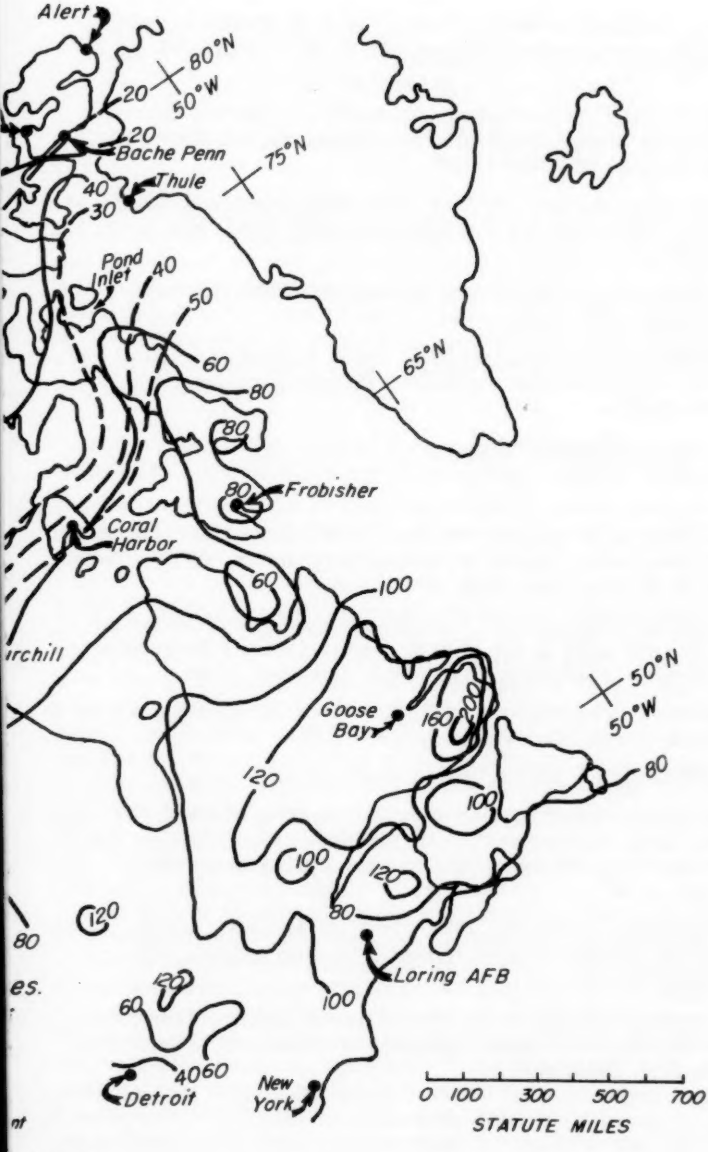
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FIG. 4

REFERENCES

1. "The Arctice: Challenge to the Air Force," by J. O. Fletcher, Col., USAF, Air University Quarterly Review, vol. 6, no. 3, Fall 1953, pp. 52-62.
2. "Arctic Study Project," (Unpublished manuscript), by Arctic, Desert, Tropic Information Center, Research Studies Institute, Air University, USAF, vol. 2, chap. 8, 1956.
3. "Navigating the Polar Routes," by E. P. Pedersen, Scandinavian Airlines System, Aircraft Observer, Air Training Command, USAF, vol. 3, no. 4, Fall 1956, pp. 26-30.
4. "Detailed Report, Project 572-55," by Headquarters 18th Air Force (TAC), vol. 1, Aug. 1955, 3 vols.
5. "Personal Observation—DEW Line, 1956," by D. A. Shaw, Lt. Col., USAF, Arctic, Desert, Tropic Information Center, Research Studies Institute, Air University, USAF.
6. "Use of Ice as a Load Supporting Surface," by K. A. Linell, Arctic Construction and Frost Effects Laboratory, Corps of Engineers, U. S. Army, 1950, p. 6.
7. "Airfields on Floating Ice Sheets, For Regular and Emergency (Aircraft) Operations," by A. Assur, Report 36, preliminary edition, SIPRE, Corps of Engineers, U. S. Army, Jan. 1956, p. 12.
8. "Report of Investigations, 1946-47," Investigations of Construction and Maintenance of Airdromes on Ice, Arctic Construction and Frost Effects Laboratory, Corps of Engineers, U. S. Army, May 1948, plate No. 5.
9. "Insulating Effect of a Snow Cover on the Growth of Young Sea Ice," by B. E. Holtsmark, Arctic, Winter 1955, p. 60.
10. "Airfields on Floating Ice Sheets," by A. Assur, p. 19.
11. "Preliminary Report—Investigations of Sea Ice Bearing Strength and Trafficability," by P. W. Pomeroy, C. E. Molineaux, and O. S. Lee, Air Force Cambridge Research Center (ARDC) and Hydrographic Office (USN), Aug. 1955, p. 4.
12. "Personal Experience—DEW Line 1956," by M. S. Maxwell, Arctic, Desert, Tropic Information Center, Research Studies Institute, Air University, USAF.
13. Glossary of Arctic and Subarctic Terms, by Arctic, Desert, Tropic Information Center, Research Studies Institute, Air University, USAF Publication A-105, Sept. 1955, p. 87.

Discussion of
"AIRFIELDS ON PERMAFROST"

by Kenneth A. Linell
(Proc. Paper 1326)

K. B. WOODS,* M. ASCE.—In discussing this paper mention is made, first, of a number of references pertaining to the engineering significance of permafrost; second, attention is directed to several of the important contributions made in the paper; third, some information is added of possible engineering significance with respect to areas of severe seasonal frost and discontinuous permafrost; and finally, considerable emphasis is placed on the importance of site selection for engineering structures in both permafrost as well as seasonal-frost regions.

Engineering Significance of Permafrost

Attention is directed to those interested in delving more deeply into the problem of Airfields on Permafrost to the outstanding work done by the Arctic Construction and Frost Effects Laboratory under the direction of the author. Chapters 2, 3, 4, and 6 of the Engineers' Manual of Arctic and Subarctic Construction, Part XV[1] will be found especially helpful. Related closely to permafrost for airfields is the subject of deep-frost penetration. This subject, too, is dealt with very well in the Engineers' Manual on "Airfield Pavement Design for Frost Conditions."[2] Other important contributions from the Frost Effects Laboratory include a report by Haley on the cold-room studies.[3] Hennion[4] has contributed a list of definitions of Frost and Permafrost terms. Some excellent information on Arctic construction in general and other Northern regions has also been made available through engineering journals such as Engineering News-Record, Civil Engineering, Military Engineer, the Engineering Journal of Canada, and others.[5,6,7,8,9] The results of engineering investigations and other work performed in Alaska are also worthy of mention.[10,11,12,13,14]

The work of Canadian engineers and other investigators on permafrost has been of great value to the engineering programs in Greenland, Alaska, and other Northern areas. Legget has reported on some of the work of the National Research Council of Canada,[15] while Hardy[16] and D'Appolonia[17] have placed considerable emphasis on foundation design in permafrost. Some railroad experiences in permafrost are reported by the Canadian National Railways.[18] Crawford and Boyd[19] and Crawford[20] have discussed climatic factors influencing permafrost and frost penetration while Potzger and Courtemanche[21] made an evaluation of certain aspects of vegetation on permafrost. The climatological atlas of Canada by Thomas[22] is, of course, a "must" for engineering design in that country.

The Snow, Ice, and Permafrost Research Establishment continues as an excellent source of translations on permafrost[23,24] as well as bibliographies[25,26] and reviews.[27]

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Problems Associated with Deep Frost Penetration

One of the most important contributions in the Linell paper is the material which shows that pavement thicknesses required to protect against weaknesses resulting from thaw are less in the extreme North than for less northerly regions. In Fig. 2, the author demonstrates this fact well in comparing depth of freeze or thaw at Thule, Greenland, with similar data at Fairbanks, Alaska.

The newly constructed Quebec, North Shore and Labrador Railroad, located in eastern Quebec and Western Labrador,[29,30] furnishes some interesting examples relating to this point. For reasons of expediency, it was necessary on this project to continue construction 24 hours each day for approximately two years. Deep snow and long periods of very cold weather precluded anything but very general soil analysis and as a result some sections of the grade were located in frost-susceptible soils. Fortunately, the soils of the Labrador Plateau are predominantly granular, but some lacustrine soils of silt size, which can be associated with certain types of muskeg, are to be found. Also some of the glacial gravels and sands contain excessive amounts of frost-susceptible "fines."

Out of a total length of 356 miles, a total of something less than one mile of frost heaves occured. These sections are located mostly between Mile 95 to Mile 120 and Mile 242 to Mile 267. Table I records the general location and magnitude of the heaves on this project as of May 1956.

Table I[32] Note on frost heaves reported in May 1956

Heaves between 3 and 5 in.

A total of 1800 ft of track involved in 35 locations

13 locations between Mile 95 and Mile 120
7 locations between Mile 227 and Mile 242
9 locations between Mile 242 and Mile 267

Heaves in excess of 5 in.

A total of 1200 ft of track involved in 16 locations

2 locations between Mile 120 and 138
4 locations between Mile 227 and 242
7 locations between Mile 242 and 267

Differential frost heaving occurs, almost in every instance, at the intersection of cut and fill sections. Differential movements of as much as six inches are common. A planned program of side drainage and excavation and

32. Personal communication from Robert Pryer, Soils Engineer, Quebec, North Shore and Labrador Railroad, Seven Islands, Quebec, Canada.

wasting of the frost-susceptible materials will solve the problem in due course of time. At present, the need for attention of maintenance crews is almost constant during the frost-penetration period and again during the long-thaw period. Shims are used to raise the track on either side of a heave as freezing progresses; they must be removed gradually as thawing progresses in the spring.

Table II[33] reports frost-penetration data at Mile 266 under various snow and vegetative cover under conditions of a freezing index of about 4700 degree days.

Table II (Reference 33) Frost Penetration Measurements

Location	Soil	Approximate Freezing Index	Measured Depth of Frost Penetration
M 266 Cut Section Part Snow Cover	Fine Gravel Till	4700	7-8 ft
M 266 Fill section Part Snow Cover	Fine Gravel Till	4700	10 ft
M 266	Muskeg Undisturbed with snow	4700	1 ft

Freezing Index: The cumulative total of degree-days below 32°F for a year.

With a total ballast thickness of about two feet, this railroad project points up the seriousness of the frost problems in a region located just south of permafrost and is a confirmation of Mr. Linell's thesis that the deep frost penetration region is a difficult one.

Frost-Zone Boundaries

The author presents construction frost zones of North America but restricts the usage of the boundaries marked in Fig. 3 "---bituminous pavement kept clear of snow, and soil moisture content of 5%." The idea has considerable merit when used with the author's state limitations. This region represents a highly populated area of the sub-Arctic in North America.

Improved boundaries, which could be used with greater security and with fewer limitations, might be developed if the additional variables of soils, vegetation, and precipitation could be evaluated. Sufficient knowledge of the engineering characteristics of soils, including frost susceptibility, is available to estimate the influence of this variable. The same is true for precipitation and vegetation.

33. Data through courtesy of Robert Pryer, Soils Engineer, Quebec, North Shore and Labrador Railroad, and William Eden, National Research Council, Ottawa, Canada.

The importance of these variables, however, can hardly be overemphasized. A further inspection of Table II shows a range from one foot to ten feet of measured depth of frost penetration under three different types of exposure and in a severely cold climate.

These same variables, precipitations (snow covers) and vegetations, undoubtedly have important and far-reaching influence on permafrost. To illustrate, attention is called to Mr. Linell's Fig. 3 which is based on a non-snow and non-vegetative cover.

The town of Hay River, Canada, located on the south shore of Great Slave Lake, is properly shown in the "seasonal frost zone" of Linell's Fig. 3, even though large islands of permafrost occur several miles south of Hay River. Using again the Quebec, North Shore and Labrador Railroad as an example in the Labrador region, Linell's boundary between permafrost and seasonal frost are moderately correct, at least so far as experiences on this project are concerned, and when using "bituminous pavement kept clear of snow, as a criterion. Actually, continuous permafrost occurs quite a distance north of the boundary shown in Fig. 3. In all probability the reason for this discrepancy can be accounted for because of the occurrence of a deep muskeg cover and of deep winter snows.

As a result of the observations made by the author and of others in parts of Canada and Alaska, it is suggested that the line on Fig. 3 which defines the southern limit of permafrost "with a thaw greater than ten feet" is likely to vary from region to region from that indicated depending upon the amount and type of vegetation, the time of occurrence, and amount of snowfall, despite the author's stipulation of ". . . bituminous pavements kept clear of now. . ."

Site Selection

In the paper, "Airfields on Permafrost," the author correctly assumed the worst conditions of frost or permafrost in establishing design criteria. Obviously, critical attention must always be given to site selection so that the potentially worst conditions can be avoided if at all possible. A great deal has been written about site selection in regions of permafrost and deep frost penetration. It should be kept in mind, however, that in the glaciation portion of North America, gravel deposits in the form of terraces, out-washes, and other landforms occur frequently and sometimes are in abundant supply. Design of almost any structure, including airfields, can follow substantially the same practices used in more southern regions if clean gravels without segregated ice can be located for a given structure. Site selection, therefore, in these vulnerable areas of deep frost penetration and permafrost should always occupy the highest priority. Design for the worst conditions would be required then, only in isolated instances where construction becomes necessary on a poor site for reasons other than sound engineering judgment.

SUMMARY

To sum up this discussion, it should be pointed out:

1. Design for conditions of permafrost containing ice segregation is still a major problem.

2. The author points out correctly that design for conditions of deep frost penetration are actually more severe than for conditions of permafrost, assuming the worst conditions for a site in both cases.

3. The importance of soil texture, vegetative and muskeg covers, and the amount of snow all combine to create variation in the southern limit of permafrost, these variables must be considered in using the limit indicated in the author's Fig. 3.

4. The importance of site selection should never be underestimated since good sites containing deep beds of clean gravel without segregated ice can frequently be found; design requirements for such sites are substantially the same as those for non-frost regions in the south.

The author has presented a timely and very important paper of considerable engineering significance.

REFERENCES

1. Engineering Manual for Military Construction, Corps of Engineers, Department of The Army, Arctic and Subarctic Construction, Part XV, October 1954: Chapter 2, Site Selection and Development; Chapter 3, Runway and Road Design; Chapter 4, Building Foundation; Chapter 6, Calculation Method for the Determination of Depths of Freeze and Thaw in Soils.

2. Engineering Manual for Military Construction, Corps of Engineers, Department of The Army, Airfield Pavement Design for Frost Conditions, Part XII, Chapter 4, April 1951.

3. "Cold-Room Studies of Frost Action in Soils, A Progress Report," by James F. Haley, Highway Research Board, Bulletin No. 71, Publication No. 262, Washington D. C., 1953.

4. "Frost and Permafrost Definitions" by Frank Hennion, Highway Research Board Bulletin No. 111, pp. 107-110, Washington D. C., 1955.

5. "Prefabricated Structures Used for Greenland Air Base," Civil Engineering vol. 23, p. 198, March 1953.

6. "Greenland-Thule Air Base Construction," Engineering News-Record, p. 21, October 2, 1952.

7. "Greenland-Thule Airbase Correction," Engineering News-Record, p. 11, December 10, 1953.

8. "Greenland Bases to Get More Steel Structure," Engineering News-Record, p. 24, August 6, 1953.

9. "Arctic Engineering Know-How Gets Acid Test at Thule," Civil Engineering vol. 23, pp. 585-589, September 1953.

10. "Arctic Engineering Requires Knowledge of Permafrost Behavior," G. W. Rathjens, Civil Engineering, vol. 21, no. 11, November 1951.

11. "Arctic Tower Foundations Frozen into Permafrost," P. W. Roberts and F. A. F. Cooke, Engineering-News-Record, vol. 144, no. 6, February 9, 1950.

12. "Alaska's Permafrost Gets Expert Attention" Engineering News-Record, December 14, 1950.

13. "Anchored Foundation Resists Frost Heave," D. B. McKinley, Civil Engineering, vol. 22, no. 2, February 1952.

14. "The Canning River Region, Northern Alaska," Professional Paper 109. U. S. Geological Survey, Washington, D. C., pp. 150-155, E. deK. Leffingwell, 1919.

15. "Permafrost Research," by R. F. Legget, Arctic Journal, Arctic Institute of North America, vol. 7, 1954.

16. "Permanently Frozen Ground and Foundation Design, Part I," by R. M. Hardy, The Engineering Journal (Canada), vol. 29, no. 1, pp. 4-7, 1946.

17. "Permanently Frozen Ground and Foundation Design, Part 2," by E. D'Appolonia, The Engineering Journal (Canada), vol. 29, no. 1, pp. 7-12, 1946.

18. "Perpetually Frozen Subsoil in Northern Canada," by Canadian National Railways, Winnipeg, Man., March 29, 1940.

19. "Climate in Relations to Frost Action," by Carl B. Crawford and Donald W. Boyd, Highway Research Board, Bulletin No. 111.

20. "Frost Penetration Studies in Canada as an Aid to Construction," by Carl B. Crawford, Road and Engineering Construction, vol. 93, no. 2, February 1955.

21. "Permafrost and Some Characteristics of Bogs and Vegetation of Northern Quebec," by J. E. Potzger and Albert Courtemanche, Rev. Can. Geographic, vol. 9, April-Sept. 1955.

22. Climatological Atlas of Canada, by Morley K. Thomas, Meteorological Division Department of Transportation, Division of Building Research, National Research Council, Ottawa, Canada, December 1953.

23. Water Supply of Railroads in Permafrost Regions, by M. I. Sumgin, N. N. Geniev, and A. M. Chekotillo, Translation 28, Snow, Ice, and Permafrost Research Establishment, Corps of Engineering, U. S. Army, October 1955.

24. Excavation of Frozen Ground, by M. I. Gal'perin, E. A. Torgonenko, and A. P. Degtiarev, Translation 53, Snow, Ice, and Permafrost, Research Establishment Corps of Engineers, U. S. Army, November 1955.

25. Bibliography on Snow, Ice and Permafrost with Abstracts, SIPRE Report No. 12, Volume XX, Snow, Ice, and Permafrost Research Establishment, Corps of Engineers, U. S. Army, January 1956.

26. Bibliography on Snow, Ice and Permafrost with Abstracts, Cumulative Index, vols. I-VIII, SIPRE Report 12, Snow, Ice, and Permafrost Research Establishment, Corps of Engineers, U. S. Army September 1955.

27. Review of Certain Properties and Problems of Frozen Ground Including Permafrost, by Purdue University Engineering Experiment Station, SIPRE Report 9, Snow, Ice, and Permafrost Research Establishment, Corps of Engineers, U. S. Army, March 1953.

28. "The Labrador Frontier," by F. Kenneth Hare, The Geographical Review, 1952.

29. "Labrador Railroad Pushes North to Iron Range," by Robert H. Dodds, Engineering News-Record, 1952.

30. "The Location and Construction of The Quebec, North Shore and Labrador Railway," by B. M. Monaghan, The Engineering Journal (Canada), 1954.

31. "Suggested Classification of Muskeg for The Engineer," by Norman W. Radforth, The Engineering Journal, The Journal of The Engineering Institute of Canada, November 1952.

32. Personal communication from Robert Pryer, Soils Engineer, Quebec, North Shore and Labrador Railroad, Seven Islands, Quebec, Canada.

33. Data through courtesy of Robert Pryer, Soils Engineer, Quebec, North Shore and Labrador Railroad, and William Eden, National Research Council, Ottawa, Canada.

PROCEEDINGS PAPERS

The technical papers published in the past year are identified by number below. Technical-division sponsorship is indicated by an abbreviation at the end of each Paper Number, the symbols referring to: Air Transport (AT), City Planning (CP), Construction (CO), Engineering Mechanics (EM), Highway (HW), Hydraulics (HY), Irrigation and Drainage (IR), Pipeline (PL), Power (PO), Sanitary Engineering (SA), Soil Mechanics and Foundations (SM), Structural (ST), Surveying and Mapping (SU), and Waterways and Harbors (WW), divisions. Papers sponsored by the Board of Direction are identified by the symbols (BD). For titles and order coupons, refer to the appropriate issue of "Civil Engineering." Beginning with Volume 82 (January 1956) papers were published in Journals of the various Technical Divisions. To locate papers in the Journals, the symbols after the paper numbers are followed by a numeral designating the issue of a particular Journal in which the paper appeared. For example, Paper 1113 is identified as 1113 (HY6) which indicates that the paper is contained in the sixth issue of the Journal of the Hydraulics Division during 1956.

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c. Discussion of several papers, grouped by Divisions.

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